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ON THE VERIFICATION OF THE PRINCIPLE OF REFLEX VISUAL SENSATIONS*

By M. S. Hollenberg

SYNOPSIS

Section I. of this communication contains a brief resumé of Allen's work on Reflex Sensations.

Section II. contains descriptions of experiments made by fatiguing the left eye with various colors and then measuring the reflex effects upon the color sensations in the right eye, which is maintained in daylight adaptation.

Section III. contains descriptions of the fatigue and reflex effects of color stimuli when applied to the right eye, the left being maintained in daylight adaptation. The direct and reflex effects of white light and darkness are also studied.

Section IV. contains theoretical discussions relative to some of Burch's experiments on fatigue, and to the brief initial overshooting of sensations when colored light is first applied to the eye. The experimental results are shown to support the trichromatic theory of Young and Helmholtz.

I.

The recent investigations[1] by Allen on the effects of retinal fatigue upon color sensations has led to the discovery of a new physiological reflex which is sensory in its nature. The rôle of this sensory reflex opens a new field in color vision as well as in the physiology of receptor end-organs.

Allen's work indicates that when light falls upon any part of either retina, the perception of the three fundamental color sensations, red, green, and violet, as measured by the critical frequency of flicker, is enhanced in both retinas. The experiments to be described in this

* Read at the meeting of The Optical Society of America, Cleveland, O., October, 1923.

[1] On Reflex Visual Sensations. J. O. S. A. and R. S. I, 7, p. 583; 1923. On Reflex Visual Sensations and Color Contrast, ibid. p. 913.

communication were undertaken to ascertain if the results obtained by Allen applied to another normal individual. This was found to be the case. The writer investigated practically the whole of the spectrum and found that in every instance his curves were identical with those of Allen.

The apparatus used to determine the critical frequency of flicker was arranged as follows:- Light from an acetylene flame passed through a rotating disk with two opposite open sectors of 90° each. The flickering light so produced, entered a spectrometer and was viewed as a spectrum in an eye-piece with adjustable shutters, which cut off all the spectrum except a narrow rectangular band of the desired wave length. By electrical means the speed of the disk was recorded when the flickering of the light in the eye-piece was perceived as a just continuous sensation. The duration in time of the light impulses which is required to produce a continuous sensation varies with the luminosity or physiological brightness of the spectrum; and when plotted with the wave lengths of the colors observed as abscissae, a curve is obtained called the persistency curve. The time on any point of this curve is referred to as the critical frequency of flicker for the corresponding wave length.

By this means a normal curve was obtained for the right eye which served as a standard of comparison for other persistency curves taken under varying conditions which will be discussed. This normal curve was checked throughout the investigation and was found to remain constant.

In fatiguing the eye a second spectrometer was used with the electric arc as the source of light. An eye-piece with adjustable shutters isolated the wave lengths with which the eye was fatigued.

It is important to note that this work was carried out in a room illuminated by diffused daylight.

The reflex curves were obtained by keeping the left eye in a state of fatigue with the particular wave length whose effect was to be investigated, and measuring the critical frequency of flicker with the right eye for which the normal had been definitely established. Between readings the right eye was kept in constant daylight adaptation.

The fatigue curves were determined by fatiguing the right eye with the desired wave length, and ascertaining the persistency curve with it, the left being always maintained in daylight adaptation.

It is thus clear that all the persistency curves to be shown were obtained with the right eye of the observer.

In each figure two curves are plotted; the normal curve for the right eye is shown as a broken line, and the reflex or fatigue curve is shown as a continuous line. At the bottom of each figure the same curves are reproduced in another form by making the normal curve a straight line and giving it an arbitrary value of 100, and reducing the fatigue and reflex curves in the same proportion. The wave length of the fatiguing color is indicated by a short vertical line in each figure.

II. REFLEX CURVES

First to be considered are the reflex curves, that is the curves obtained by the right eye when the left was fatigued by a definite wave length. The persistency curves taken were selected to represent the whole spectrum. The data of all the curves discussed in this section are given in Table 1.

The effect produced upon the right eye by preventing all stimulation of the left by blindfolding it, was first obtained. The curves in Fig. 1 show that by removing all stimulation of the left eye, the retina of the right eye reacts more sluggishly than normal, with the result that the persistency curve lies wholly above the normal with the same physical spectrum, indicating that its physiological brightness is reduced below its normal value. It is evident that the right eye is rendered less sensitive to the whole spectrum by removing the stimulation produced upon the left eye by diffused daylight.

Conversely, when the left eye is stimulated by white light more intense than diffused daylight, e.g. white light from the arc, which was used in this experiment, the right eye, as shown by the persistency curves in Fig. 2, becomes much more sensitive to every color of the spectrum, and there is in consequence depression of the whole curve below the normal. In both figures, 1, and 2, the reduced curves show a marked threefold division corresponding to the colors, red, green-yellow and violet.

In the next experiment the left eye was fatigued with red light of wave length .687μ. The curve for the right eye in Fig. 3 is characterized by three depressions below the normal, which are better shown in the reduced curves at the bottom of the figure. These occur in the regions corresponding to the red, green, and violet colors. The depressions are not confined to those colors but extend into the surrounding regions

TABLE 1. *Reflex Curves*

λ	Normal sec.	White Light sec.	Darkness sec.	.687μ sec.	.660μ sec.	.589μ sec.	.572μ sec.	.540μ sec.	.450μ sec.	.410μ sec
.74μ	0.0340	0.0308	0.0400	0.0315	0.0333	0.0316	0.0338	0.0326	0.0324	0.0324
.72	.0282	.0265	.0305	.0266	.0281	.0264	.0280	.0268	.0265	.0266
.70	.0240	.0228	.0260	.0226	.0240	.0224	.0237	.0226	.0224	.0228
.68	.0202	.0189	.0219	.0190	.0205	.0195	.0201	.0194	.0194	.0192
.66	.0172	.0166	.0191	.0163	.0175	.0164	.0170	.0166	.0164	.0167
.64	.0160	.0152	.0172	.0157	.0163	.0149	.0157	.0156	.0157	.0161
.62	.0151	.0142	.0168	.0142	.0153	.0137	.0148	.0147	.0145	.0146
.59	.0148	.0137	.0163	.0139	.0151	.0131	.0145	.0140	.0142	.0139
.55	.0155	.0143	.0166	.0147	.0153	.0141	.0152	.0148	.0148	.0149
.53	.0166	.0154	.0173	.0155	.0164	.0151	.0164	.0151	.0152	.0161
.50	.0210	.0200	.0216	.0201	.0205	.0204	.0210	.0207	.0207	.0201
.48	.0255	.0240	.0289	.0244	.0252	.0243	.0254	.0249	.0248	.0240
.46	.0310	.0279	.0335	.0293	.0310	.0304	.0309	.0301	.0303	.0295
.44	.0350	.0326	.0415	.0342	.0343	.0332	.0349	.0337	.0342	.0322
.42	.0420	.0402	.0507	.0401	.0410	.0401	.0414	.0400	.0401	.0382

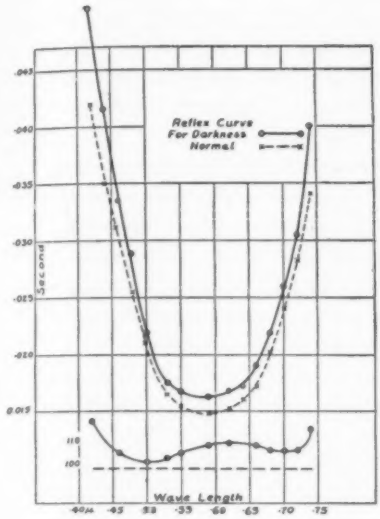

FIG. 1
Reflex Curve for Darkness.

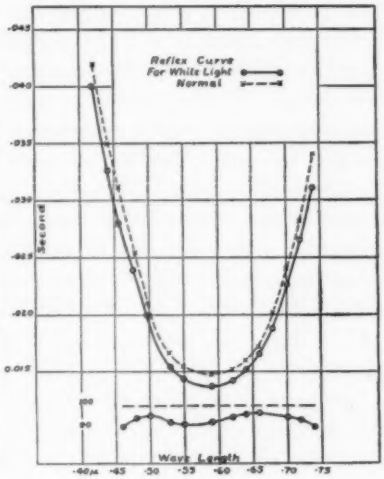

FIG. 2
Reflex Curve for White Light.

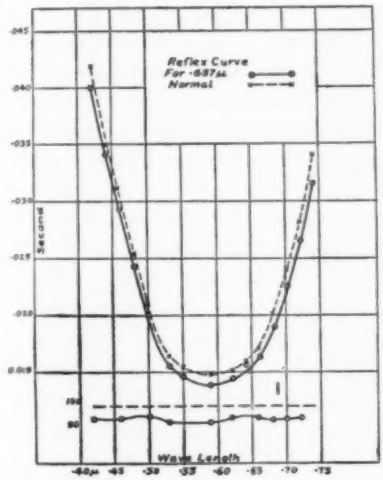

FIG. 3
Reflex Curve for .687μ.

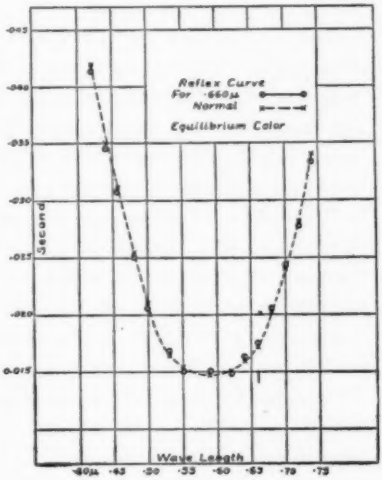

FIG. 4
Reflex Curve for .660μ.

as well. The conclusion to be drawn is that by a sensory reflex process the effect of fatiguing the left eye with red light of wave length .687μ, was transferred to the right eye, and there resulted in an enhancement of the brightness of three spectral regions. The three depressions are separated by two points at about .64μ and .52μ where the normal and abnormal curves approximate each other. The curves obtained when the wave lengths .660μ and .572μ were employed as fatiguing stimuli are shown in Fig. 4 and Fig. 6, respectively. They have no depressions, but coincide with the normal curve throughout their length. Allen[2] has named these wave lengths equilibrium colors. In the paper just cited Allen found the second equilibrium color at .570μ, but subsequently[3] he determined it more exactly at .572μ.

In Fig. 5 is shown the reflex effect of the yellow color .589μ. This is about the brightest part of the spectrum and gave the greatest reflex effect obtained, i.e. the greatest enhancement of the red, green, and violet sensations. The three depressions in this curve are well marked and the coincidence or division points are at the wave lengths .50μ and .67μ.

In Figs. 7, 8, and 9 are shown the reflexes obtained with the fatiguing colors .540μ, .450μ, and .410μ, respectively. All these curves, like the above, exhibit the usual three depressions, indicating enhancement of the three color sensations.

From a consideration of the above curves, it is evident that stimulation of the left eye by any color has but one effect upon the retina of the right eye, viz., the latter is so altered that the sensitiveness of the three fundamental color sensations is increased. The equilibrium colors are exceptions to this statement; for fatiguing the left eye with these produces no effect upon the right eye.

One striking feature especially noticeable is that while the luminosity of violet of wave length .410μ is about one seven-hundredth of that of yellow .589μ, the depressions produced by the latter color are but slightly greater. This shows that the magnitude of the reflex effect is not a direct function of the physiological brightness of the stimulus.

Only two of the equilibrium colors, .660μ and .572μ were verified. The remaining four found by Allen[4] at the wave lengths .520μ, .505μ, .480μ, and .425μ, were not tried, as the general verification of his results was so complete.

[2] On Reflex Visual Sensations, Loc. cit., p. 610.
[3] Reflex Visual Sensations and Color Contrast. J. O. S. A. and R. S. I. 7, p. 921; 1923.
[4] J. O. S. A. and R. S. I., 7, p. 611; 1923.

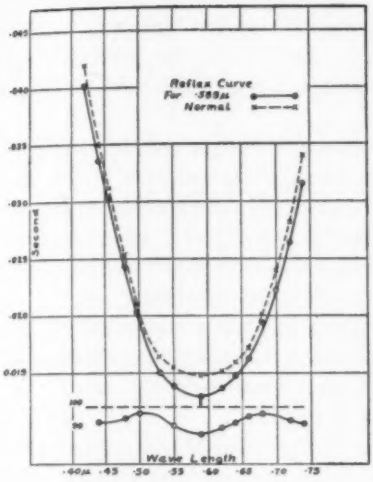

FIG. 5
Reflex Curve for .589μ.

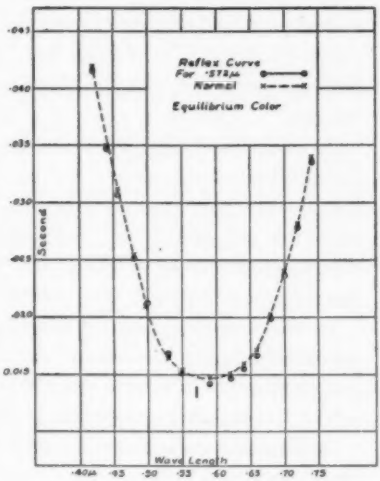

FIG. 6
Reflex Curve for .572μ.

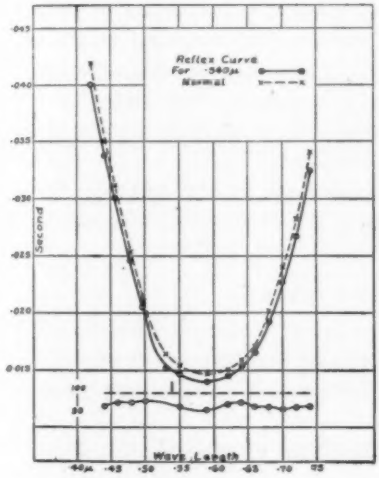

FIG. 7
Reflex Curve for .540μ.

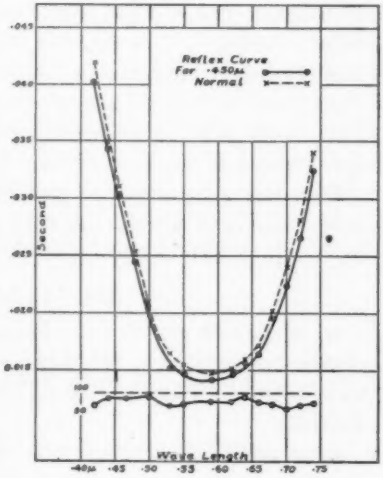

FIG. 8
Reflex Curve for .450μ.

It will be noticed in the preceding curves that while fatigue of one eye always reflexly enhances the perception of the spectrum in the other in the three regions red, green, and violet, the predominant enhancement is in the sensations complementary to the color used for fatigue.

In connection with these reflex effects some observations by Edridge-Green[5] are of interest. "When one eye is fatigued with a spectral colour, the other eye being kept closed and covered with the hand, and then the eye which has been fatigued is closed and a white surface viewed with the unfatigued eye, this appears as if it were mixed with the colour of the light used which was fatiguing the other eye."

In these observations of Edridge-Green the reflex effects of fatigue transferred from one eye to the other were complicated by darkness adaptation which affects the different sensations unequally, as may be seen by examining the curves in Figs. 1 and 10.

Edridge-Green also directs attention to the possibility of error arising from comparing observations made simultaneously by a fatigued eye and by the other which is assumed, often erroneously, to remain in its normal condition.

The presence of these reflex effects in the unfatigued eye may possibly invalidate some of the observations of Burch in his experiments on fatigue. In one of his papers[6] he thus describes his method of making observations: "I then exposed my eye for a few seconds to the extremely bright light in the focus of the lens, and immediately afterwards looked through a single-prism spectroscope illuminated by the light of the sky, comparing the results with those given by the other eye, which had not been exposed to the light."

Darkness adaptation of and reflex effects in the unexposed eye may easily have altered the appearance of colors which was assumed by Burch to remain quite normal.

III. FATIGUE CURVES

We shall now consider the fatigue curves, or the persistency curves obtained by the right eye when it was fatigued by colors of definite wave lengths. The data for all the curves in this section are given in Table 2.

As in the reflex curves, it was decided first to ascertain the effect of darkness adaptation of the observing eye. This condition was pro-

[5] New Researches in Colour Vision, Lancet, p. 360; 1922.

[6] On Artificial Temporary Colour Blindness. Phil. Trans. B., *191*, p. 4; 1899.

TABLE 2. *Fatigue Curves*

λ	Normal sec.	White Light sec.	Darkness sec.	.687μ sec.	.660μ sec.	.589μ sec.	.572μ sec.	.540μ sec.	.450μ sec.	.410μ sec.
.74μ	0.0340	0.0390	0.0357	0.0361	0.0335	0.0355	0.0341	0.0306	0.0321	0.0320
.72	.0282	.0325	.0300	.0302	.0282	.0301	.0283	.0257	.0266	.0269
.70	.0240	.0280	.0258	.0251	.0240	.0258	.0242	.0220	.0235	.0227
.68	.0202	.0232	.0216	.0209	.0205	.0210	.0201	.0191	.0205	.0191
.66	.0172	.0209	.0187	.0171	.0174	.0176	.0174	.0168	.0177	.0169
.64	.0160	.0180	.0171	.0155	.0159	.0167	.0160	.0157	.0165	.0152
.62	.0151	.0167	.0163	.0143	.0154	.0160	.0150	.0150	.0157	.0145
.59	.0148	.0160	.0159	.0138	.0150	.0159	.0146	.0148	.0150	.0136
.55	.0155	.0171	.0171	.0148	.0154	.0173	.0154	.0171	.0160	.0145
.53	.0166	.0179	.0190	.0160	.0185	.0184	.0165	.0181	.0166	.0157
.50	.0210	.0231	.0237	.0210	.0205	.0201	.0209	.0209	.0222	.0210
.48	.0255	.0276	.0283	.0250	.0252	.0241	.0233	.0233	.0263	.0265
.46	.0310	.0356	.0341	.0298	.0309	.0304	.0310	.0286	.0328	.0330
.44	.0350	.0388	.0387	.0339	.0342	.0332	.0347	.0326	.0377	.0370
.42	.0420	.0458	.0451	.0404	.0409	.0401	.0419	.0392	.0430	.0435

duced by blind-folding the right eye and removing the eye shield only while a reading in the spectroscope was being taken. The left eye was in normal daylight adaptation, which was the case with all curves described in this section. From the curve in Fig. 10 we see that the absence of all stimulation from the right eye elevates the whole persistency curve above the normal, indicating that the physiological brightness of the spectrum is diminished, and that the sensitiveness of the retina for all color impressions is depressed.

If this curve be compared with that in Fig. 1 for the apparent reflex effect of darkness adaptation of the left eye, the two will be observed to be similarly elevated above the normal. The direct effect of darkness adaptation of the retina, and the transferred effect of darkness adaptation of the other retina, operate in both cases to depress the sensitiveness of both retinas to all colors.

The converse of this experiment was now tried by subjecting the retina to white light of great intensity from an arc lamp. The curve obtained by the right eye, Fig. 11, was again above the normal in all parts, indicating fatigue of all three sensations.

It is to be observed that the effects of darkness and bright white light upon the observing eye are almost identical. Thus we see that the eye is best adapted for the perception of color stimuli in diffused daylight; and that its power of perception is depressed either by very strong stimulation or by the absence of stimulation, i.e. by darkness.

The curve obtained by fatiguing the observing eye with red light of wave length .687μ is shown in Fig. 12. The effect produced is an elevation or fatigue effect in the part corresponding to red; and two depressions below the normal indicating reflex enhancement of perception in the violet and green. The two points which almost correspond to the normal are found as before at the wave lengths .66μ and .50μ.

The right eye was fatigued in turn with the equilibrium colors .660μ and .572μ. The curves coincided with the normal like those shown above in Figs. 4 and 6. This indicates that fatigue with equilibrium colors produces neither depression nor enhancement of the color sensations. At these points the direct and reflex effects of the color stimulus balance each other with the result that the normal physiological brightness of the spectrum is undisturbed.

The color between these two equilibrium points selected for the fatiguing stimulus was the wave length .589μ. The resulting persistency

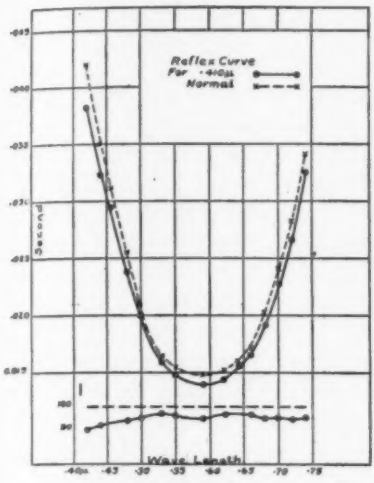

FIG. 9
Reflex Curve for .410μ.

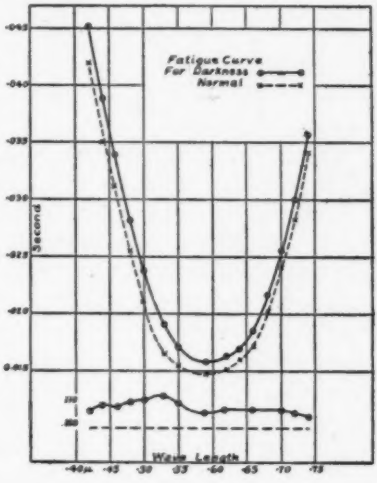

FIG. 10
Fatigue Curve for Darkness.

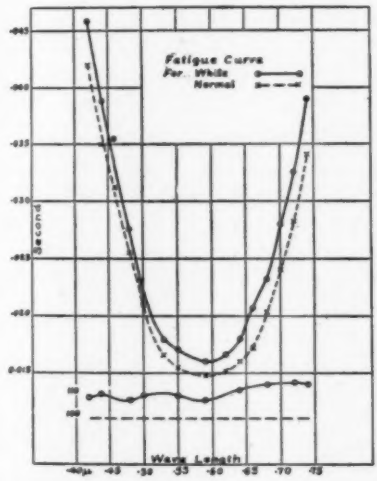

FIG. 11
Fatigue Curve for White.

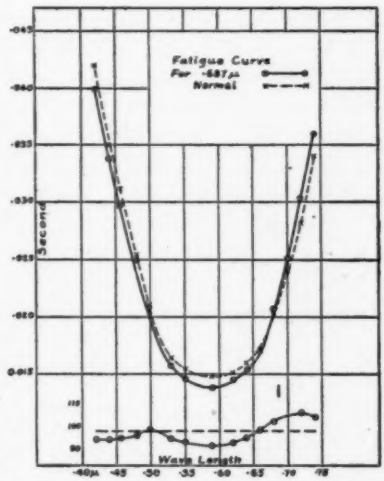

FIG. 12
Fatigue Curve for .687μ.

curve, in Fig. 13, is characterized by two prominent elevations in the red and green, and a depression in the violet, separated from each other by the wave lengths .50μ and .66μ. The two elevations prove that yellow light directly affects the red and green sensations, and reflexly the violet. Yellow is thus seen to be compound in its nature.

The next color used for fatigue was green of wave length .540μ. The effect produced by this color, as shown in Fig. 14, is a fatigue elevation in the part corresponding to green, and reflex depressions in those corresponding to red and violet. The three parts are separated by the wave lengths .50μ and .66μ as before. Green, like red, is a simple sensation and therefore fatigues only one part of the spectrum.

The effect produced by blue of wave length .450μ is shown in Fig. 15. Two fatigue elevations are caused in the green and violet regions of the curve, and a reflex depression in the part corresponding to red. Blue, like yellow, is therefore shown to be compound in its nature.

The last color tried was violet of wave length .410μ. The curve in Fig. 16 is characterized by a fatigue elevation in the part corresponding to violet, and two reflex depressions in the parts corresponding to green and red, which are separated at the wave lengths .50μ and .66μ. As in the case of red and green, the single elevation shows violet to be a primary or fundamental sensation.

In measuring the critical frequency of flicker in the right eye when it was fatigued by very bright white light, observations were also made by slight indirect vision upon an adjoining area of the retina. The measurements, in Table 3, are shown graphically in Fig. 17. The curve is below the normal in all parts, showing that upon the retinal area employed, the fatiguing white light has a sensory reflex effect precisely the same as was found by transference from one eye to the other, as shown in Fig. 2. This proves that fatigue upon one area of a retina enhances color vision in adjoining areas by reflex action. The curve therefore confirms Allen's[7] results by which he explained the phenomena of contrast.

IV. THEORETICAL CONSIDERATIONS

In the first series of reflex curves, stimulation was confined to the left eye, and the reflex effect, which occurred in both eyes, was isolated in the right. We are justified therefore in concluding that every ray of light excites in the visual apparatus reciprocal or reflex effects which

[7] Reflex Visual Sensations and Color Contrast. J. O. S. A. and R. S. I., 7, p. 929, 1923.

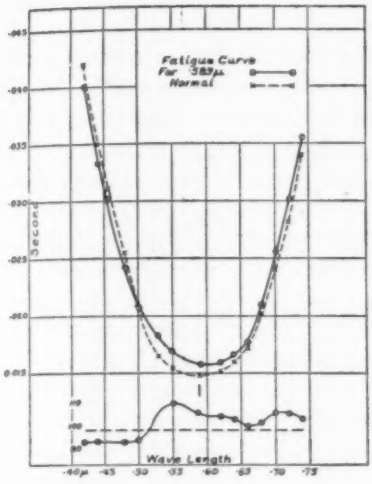

FIG. 13
Fatigue Curve for .589μ.

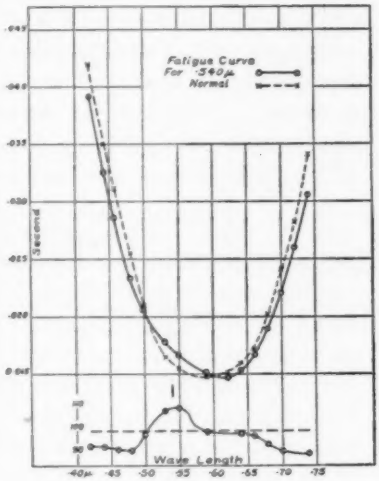

FIG. 14
Fatigue Curve for .540μ.

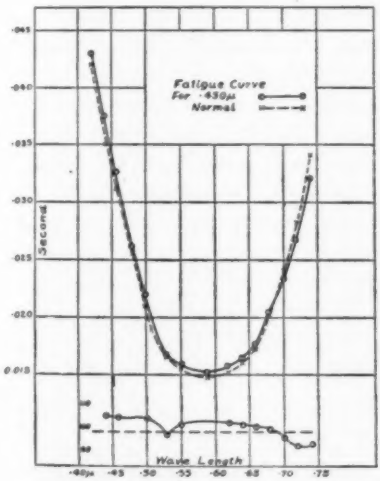

FIG. 15
Fatigue Curve for .450μ.

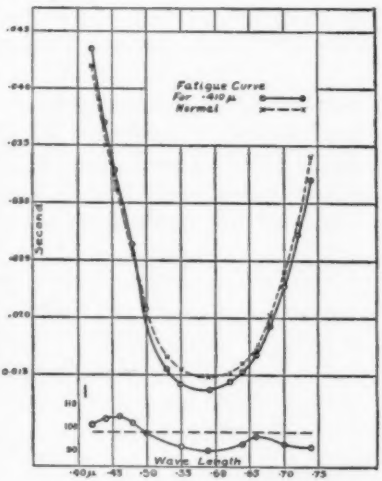

FIG. 16
Fatigue Curve for 410μ.

enhance the physiological brightness of the three parts of the spectrum, red, green, and violet.

In the second series of fatigue curves, the elevations are the algebraic sums or the net results, of fatigue and reflex action, the balance being in favor of fatigue in the sensation or sensations directly affected.

TABLE 3. REFLEX CURVE FOR WHITE LIGHT

λ	Normal	White Light	λ	Normal	White Light
	SEC.	SEC.		SEC.	SEC.
.74μ	0.0340	0.0331	.55μ	0.0155	0.0145
.72	.0282	.0275	.53	.0166	.0157
.70	.0240	.0233	.50	.0210	.0204
.68	.0202	.0194	.48	.0255	.0248
.66	.0172	.0165	.46	.0310	.0300
.64	.0160	.0151	.44	.0350	.0343
.62	.0151	.0144	.42	.0420	.0409
.59	.0148	.0140			

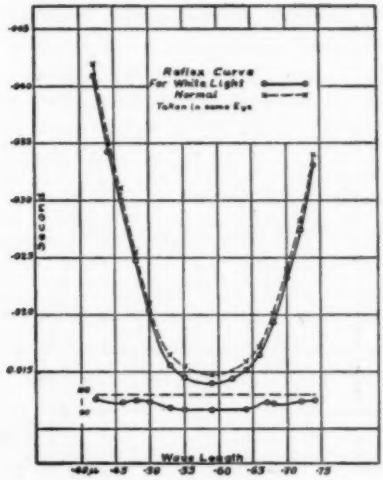

FIG. 17

Reflex Curve for White Light on Area adjoining fatigued Area.

The depressions indicate the parts of the spectrum reflexly enhanced. In both sets of curves the predominant enhancement occurs in the sensations complementary to the fatiguing color.

With this conclusion some of Burch's experiments on fatigue agree. Hartridge[8] refers briefly to these by saying that Burch found the complementary color actually to appear more vivid than usual after fatigue with any color.

In the paper by Burch, to which reference has been made above,[9] he mentions certain observations made in his flower garden, after fatiguing his eye with excessively bright colors from sunlight. Only one observation is quoted here.

"During the condition of purple-blindness all red, purple, or blue flowers look nearly black, but the grass appears of a brilliant rich green, beside which its color to the normal eye is dirty by comparison." It will be remembered that purple is the complementary of green.

Afterward in continuing his experiments on spectral colors in his laboratory, Burch concludes that "the temporary abolition of any one color sensation is without effect on the intensity of the remaining color sensations, neither increasing nor diminishing them unless they have been to some extent implicated in the light used for producing color-blindness."

In the first experiments Burch was in his garden in bright daylight while his eye was being fatigued; in the second he was in his dark laboratory. In daylight he found the complementary of the fatiguing color to be enhanced in brightness as the quotation on the effect of purple-blindness, for example, plainly shows. In the dark laboratory, on the contrary, the complementary color was unaffected.

The first observations conform to the experimental results discussed in this paper. Allen[10] has shown that the transferrable effect of darkness adaptation from one eye to the other balances and thereby conceals the reflex enhancement of the complementary of the fatiguing color, a result which explains the negative conclusions of Burch from his second experiments.

In Bidwell's experiment,[11] by which he showed that a red color, viewed intermittently by rotating a white and black sectored disk, loses its original hue and appears green, we have a vivid example of the visibility of the reflex enhancement of the complementary color. The speed of rotation necessary to produce this effect shows that the

[8] In Starling's "Human Physiology" (3rd Ed.) p. 571.

[9] See also, Parson's "Colour Vision," p. 113.

[10] On Reflex Visual Sensations, loc. cit. p. 607.

[11] Proc. Roy. Soc., *61*, p. 269; 1896. Also Allen, On Reflex Visual Sensations, loc. cit. p. 619.

flash of red light stimulates the eye for from 0.015 sec. to 0.02 sec., which is about the same interval of time as that of the most rapid motor reflex.

But before the enhancement of the green sensation occurs, the red itself becomes much brighter, as Bidwell observed. This can only be interpreted as the reflex enhancement of the red sensation which takes place in a shorter interval of time than the enhancement of the green under the influence of red light.

This effect has been studied, among others, by Broca and Sulzer,[12] who found that when a color of constant intensity falls on the retina the sensation which it produces does not attain its permanent value immediately, but rises rapidly to an intensity much greater than the normal to which it then similarly falls. In the case of red the overshooting of brightness, as it has been called, causes that color to appear about twice its normal brightness, green a little brighter than normal, and blue about five times its normal intensity. The amount of overshooting depends upon the luminosity of the stimulus.

The curves obtained by Broca and Sulzer for red, green, and blue, are reproduced in Fig. 18. The numbers on the curves, and the dotted horizontal lines on the right side of the figures, indicate the final steady values of the colors employed.

From these it is seen that for a very short interval of time the stimulus is unable to produce a sensation of brightness equal to the normal value. The intensity curve makes a sharp bend upward until the normal value is reached when it 'overshoots' rapidly. These characteristics are shown in the curves for all three colors.

In the case of the curve for blue, the first inflection, which probably marks the beginning of the reflex enhancement, occurs in 0.0156 sec., which is about the value Bidwell found for the development of the green reflex with a red stimulus. The sensory reflex effect, as we have shown, enhances the perception of color, and since it makes its appearance in the time estimated for the reflex to occur, it is practically certain that the overshooting in all cases is due to the initial and almost unopposed reflex enhancement of the sensations.

Now the reflex enhancement is probably of a constant value, but the direct fatigue progresses with the time of stimulation. The result is that up to 0.054 sec., in the case of blue light, the reflex enhancement preponderates over the direct fatigue, and after that the direct fatigue

[12] Comp. Rend., *2*, p. 1046; 1903. Also Luckiesh, Color and its Applications, p. 139.

increases above the reflex effect, and the physiological brightness gradually decreases. In 0.25 sec. (blue) it reaches its normal value, that is, the reflex and direct effects maintain a definite ratio towards each other.

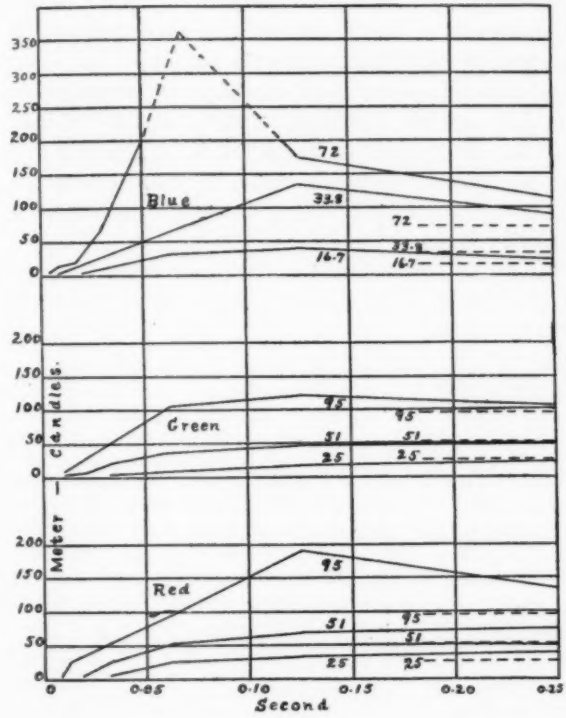

FIG. 18

Curves showing initial development of red, green, and blue sensations. (Broca and Sulzer.)

The curves also show that when the stimulus is sufficiently diminished in intensity, probably at some critical value for each color, the opposing or antagonistic direct and reflex effects, i.e., fatigue and enhancement, progress together in such a manner that the normal brightness is approached without overshooting.

The result of this application of the reflex theory is twofold; first, Broca and Sulzer's curves corroborate the reflex time as computed from Bidwell's effect; second, it affords an explanation of the overshooting of sensations which hitherto has been lacking.

The results discussed in this communication are experimental and therefore quite independent of any theory. The uniform threefold character of the elevations and depressions in the curves confirms the trichromatic nature of color vision. The color theory of Young and Helmholtz, when enlarged by the addition of Allen's principle of the reflex enhancement of sensations or the sensory reflex, is quite in harmony with the facts disclosed by the curves.

This communication forms part of a series of investigations relating to Color Vision and the physiology of the receptor end-organs now in progress in the Department of Physics of the University of Manitoba, under the direction of Professor Frank Allen, and with the financial assistance of the Honorary Advisory Council for Scientific and Industrial Research, Ottawa.

I desire to express my thanks to Professor Allen for the use of his apparatus and for his suggestions in connection with the work.

DEPARTMENT OF PHYSICS,
UNIVERSITY OF MANITOBA,
WINNIPEG, CANADA.
JANUARY 9, 1924.

Helmholtz's Physiological Optics.—The work of preparing an English translation of the third edition of Helmholtz's *Handbuch der Physiologischen Optik*, which will be published by the Optical Society of America, is now so far advanced that it is expected that the first volume will be ready by June 1924. The second and third volumes will follow as soon as they can be completed. The editor went abroad last summer especially to confer with Professor von Kries and Professor Gullstrand about the English edition of this work. An entirely new chapter on ophthalmoscopy taken from Professor Gullstrand's "Einführung in die Methoden der Dioptrik des Auges des Menschen" will be added at the end of the first volume. Professor von Kries has also consented to prepare a number of minor new contributions for the other volumes. The work will be published in approximately the same style as the original German edition, with the same illustrations, plates, etc.; and will contain references to some of the more important recent literature covering the broad domain of light and vision.

This is an expensive work to manufacture and publish, and the edition will be limited to one thousand copies. The price will not exceed $7 a volume. In order to *insure getting all three volumes*, orders should be sent without delay to the Managing Editor of the Journal of the Optical Society and Review of Scientific Instruments.

The list of those who have already subscribed has been kept, and copies will be duly forwarded to them without extra charge.

REFLEX VISUAL SENSATIONS AND ANOMALOUS TRICHROMATISM

By W. A. Anderson

SYNOPSIS

Sec. I. Introduction.—This contains a brief summary of the principle of reflex visual sensations as discovered by Allen. The author, whose vision is somewhat abnormal, sets out to determine the character of these reflexes for his abnormal vision.

Sec. II. Apparatus and Methods of Measurement.—All experiments were performed in a daylight room, using the critical frequency of flicker method. The results, which are quantitative, were obtained by making measurements on pure spectral colors.

Sec. III. Normal Curves.—Abnormal vision is shown by the character of the persistency curve, taken under normal conditions of daylight adaptation. The type of curve, which was found to be the same for both eyes, is compared with one for normal vision and one for partial red color blindness.

Sec. IV. Reflex Curves.—This contains the descriptions and results of experiments carried out by fatiguing the left eye and making measurements of the changes in the visual response of the right to light from the different parts of the spectrum.

The nature of any change in the response was always found to be an enhancement of brightness of the affected colors. Red and green were found to be more susceptible to this reflex enhancement than the violet. Certain colors, .660μ, .505μ, .425μ, and the entire region .520μ to .480μ, showed no reflex transferred to the other eye. The magnitude of the reflex was greatest for fatiguing colors near the ends of the spectrum. The effect of dark adaptation was also transferred to the other eye similarly to fatigue.

Sec. V. Fatigue Curves.—This contains descriptions and results of experiments in which the measurements were made on the fatigued eye, the other being always in daylight adaptation.

It was found that the red sensation was very difficult to fatigue, but very susceptible to enhancement. The violet showed the reverse character, and the green an intermediate position. No effect was obtained for fatigue colors, .665μ, .589μ, .570μ, and only a small effect for .520μ. The effects of darkness and strong white light are very similar, both showing fatigue characteristics.

Sec. VI. The Theoretical Considerations.—The experimental results show that every ray of light produces both a direct and a reflex effect upon all three fundamental sensations, which are shown to be red, green, and violet. The author's type of color vision is shown to be that of an anomalous trichromat, and experimental evidence is applied to give a fuller meaning to the phenomenon as well as to explain it. The principle of visual reflexes is applied to the Young-Helmholtz and Hering theories to show that the two can no longer be regarded as rival theories, but can be harmonized by this principle.

I. Introduction

In recent investigations by Allen,[1] abundant experimental evidence has been brought forth establishing a new principle of color vision, the application of which to the Young-Helmholtz theory offers simple and satisfactory explanations of many of the phenomena of color perception,

[1] J. O. S. A. & R. S. I., 7, p. 583; 1923.

which were admittedly inexplicable on the basis of the trichromatic theory.

His results show that the effect of fatiguing a given area of one retina with any spectral color, except an equilibrium one, is to lower the luminous response of that area to colors corresponding to the sensations directly affected by the fatiguing stimulus, and to enhance its response to colors exciting chiefly the complementary sensations. However, when the colors are received upon a portion of the retina adjoining the fatigued area,[2] or by the retina of the other eye, the physiological luminosity of the entire spectrum is enhanced. Thus the conclusion is drawn, that every ray of light produces two effects, a direct and a reflex. In the stimulated area of the retina, the direct action fatigues either one or two of the fundamental sensations, according as the color stimulus is simple or compound in its nature; the reflex effect enhances the luminous response of the remaining complementary sensations. It is further concluded that the reflex is transferred to the adjoining areas of the same retina, and also to the other eye, in such a way as to enhance all three sensations.

The author of this paper set out to repeat some of these observations but immediately discovered, from the character of his normal persistency curve, that his perception of light and color is somewhat abnormal. It was therefore of interest to determine the character of these direct and reflex actions of light for one of abnormal vision.

II. Apparatus and Methods of Observation

The apparatus used and the method adopted was, in most respects, the same as that employed by Allen. For the purpose of measurement the apparatus was essentially the same as that originally devised by E. L. Nichols.[3] The source of light was an acetylene flame, for which the gas was supplied at a constant pressure. The light was focused upon the slit of the collimator of a Hilger spectrometer, fitted with four prisms equivalent to three of sixty degrees each. This gave a spectrum of considerable dispersion, narrow strips of which could be isolated in a shutter eyepiece. Between the acetylene flame and the condensing lens an aluminum disk with two opposite open sectors of ninety degrees each was rotated. The speed of rotation, which was regulated by means of a brake, was electrically recorded upon a chronograph. The gas flame was enclosed on all sides, except the top, in a wooden box fitted

[2] J. O. S. A. & R. S. I., *7*, p. 913; 1923.
[3] E. L. Nichols, Am. Jour. Sci., *28*; 1884.

with a small glass window which transmitted the light to the spectrometer. This box served two purposes, first, in preventing the air currents, produced by the rotating disk, from affecting the flame, and second, in shielding the light from the observer's eyes. The spectrometer was properly screened from all extraneous light, and a shield, closely fitting about the eye, was attached to the eyepiece, thus enabling all measurements to be made under exactly the same conditions.

The spectrum used for fatiguing the eye, in the case of nearly all the reflex and also for some of the fatigue curves, was obtained from an arc light by means of a two-prism Browning spectrometer. A narrow but quite long rectangular patch of the spectrum was isolated by the shutter eyepiece. The spectrum was so intense that the colors in the middle portions of it approached whiteness in appearance. For the majority of the fatigue curves a constant deviation Hilger spectrometer was employed to furnish the fatiguing color. With this instrument the source of light for the blue and violet was always the electric arc, and for the remainder of the fatiguing colors, sometimes the arc was used, and at other times an incandescent bulb, which produced a red of about the same intensity as that of the arc spectrum. The use of the Hilger spectrometer and incandescent bulb made a more convenient arrangement of the apparatus, enabling measurements to be made within a few seconds after removing the eye from the fatiguing color.

While fatiguing one eye, or making measurements, which was always done with the right, the unused eye was directed at a neutral grey surface about ten inches away. Sometimes, when recording observations on the dim ends of the spectrum, the left eye was closed for a few seconds, which did not exceed half a minute. No difference could be detected in the time of the critical frequency of flicker, as recorded for the brighter parts of the spectrum when the left eye was closed for a few seconds, and it was assumed that the time was unaffected for the dim colors.

All the apparatus was mounted in a room well illuminated with daylight. Measurements were not attempted if it was too cloudy or dull or towards sunset, and never with artificial lighting, for Allen has shown that dim light and darkness tend to obscure the reflex action of light.

The rotating sectored disk produced a flickering sensation in the isolated patch of the spectrum, due to the rapid succession of equal intervals of color and darkness. After adjusting the speed of the motor

until the flicker was just imperceptible, the chronograph was started, and while the record was being made, which required about half a minute, the speed of the disk was varied slightly, keeping the flicker just on the point of appearing and disappearing. At least two independent records, representing the time of 120 and 400 revolutions of the disk, were made for each point, and if these did not show good agreement more readings were taken. So constant were the conditions, that the independent records gave values for the duration of a single flash, at the critical frequency of flicker, with a variation seldom greater than 0.0002 sec., except for points in the dim ends of the spectrum. The values used in plotting points in the bright parts of the spectrum were means of usually two or three independent measurements, and for the extreme violet and red the mean of about four readings was taken.

These experiments stretched over an interval of about fifteen months, most of the work being done, however, during the first three and the last five months. The curves were not necessarily taken in the order presented in this paper, although nearly all of the reflex curves were completed during the first three months and before any fatigue curves were attempted.

III. NORMAL CURVES

In making measurements for a normal curve, the following procedure was adopted. The spectrometer was set so that the shutter eyepiece isolated a narrow rectangular patch of the spectrum, the mean wave length of which was known. The spectral color was observed by the right eye, while the speed of the disk was regulated to give the critical frequency, which was then recorded. Care was taken to fixate the color directly, and to prevent the eye from wandering while judging the point of critical frequency. The eye was then rested for a minute or two, and a second chronographic record made on the same portion of the spectrum. Between the measurements made on different points in the spectrum the eye was rested in the diffuse daylight of the room for from five to ten minutes, according to the brightness of the spectral color. Since the spectrum, upon which all measurements were made, was not very brilliant, and the time required to record one reading about half a minute, the eye was not likely to become appreciably fatigued. In this way, observations were made on fifteen or more points of the spectrum.

The persistency curves, obtained by plotting wave lengths as abscissae and the persistence of vision as ordinates, show that the duration of these light impulses varies as some inverse function of the luminosity of the color observed. It was discovered by Ferry,[4] and subsequently in another manner by Porter,[5] that the duration of the sensation of undiminished brightness of a flash of light, at the critical frequency of flicker, depends only on the luminosity of the light and in no way on the wave length. The Ferry-Porter law, as it is known, is represented by the equation, $D=\frac{1}{k \log L+k_1}$, where D is the persistence of vision, L the luminosity, and k and k_1 two constants. According to this law, a lowering of the persistency curve may be interpreted as an increase and an elevation as a decrease in the luminosity of the spectrum as perceived by the eye.

Considerable difficulty was experienced at first in obtaining a satisfactory normal curve. The author was not aware that his vision was abnormal in any way, and expected to get a smooth curve as obtained by other observers of normal vision. After every set of readings, the curve proved to be irregular between .59μ and .66μ, and it was thought for a time that this was due to the writer's inexperience in making such measurements. The readings were repeated again and again, the greatest care being taken to make correct observations, yet a smooth curve was never obtained through this region. After two weeks of strenuous work and several hundred measurements the writer was forced to realize that his color vision was not completely normal. The normal curve was finally plotted showing the abnormal elevation between .59μ and .66μ, the exact character of which was accurately determined by making observations on several additional points in this part of the spectrum.

Another difficulty experienced in obtaining a satisfactory normal was the gradual lowering of the entire curve as the constant re-reading of points continued from day to day. This gradual depression of the curve, which was most pronounced during the first three weeks and before a satisfactory normal was obtained, continued to drop very slowly for several weeks more. The phenomenon appears as one peculiar to the author himself, for three other observers, using the same apparatus and working under the same conditions for several

[4] Am. Jour. Sci. *44*, 1892.
[5] Proc. Roy. Soc. *63*, 1898; *70*; 1902.

months, did not experience it. One observer was noticeably color deficient in red, while the other two were of normal color vision and obtained almost identical persistency curves. Because of this gradual lowering of the normal the readings were repeated every few days, and if any appreciable change had taken place the fatigue or reflex curves, taken since the last normal observation, were discarded. It was found, however, after about one month's work that the normal remained almost constant. During continuous work from week to week the change in the normal, if any, was always a general lowering and never

TABLE 1. *Normal Curves*

λ	Normals for Right Eye			Normal	Normal	Normal
	First	Second	Third	Left Eye	For F. A.	For A. H.
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
.740μ	0.0329	0.0309	0.0301	0.0303	0.0335	0.0386
.720	.0277	.0256	.0249	.0253	.0287	.0316
.700	.0247	.0206	.0199	.0198	.0244	.0266
.680	.....	.0171	.0158	.0162	.....	.0229
.660	.0165	.0153	.0142	.0140	.0174	.0182
.640	.0158	.0148	.0136	.0133	.....	.0160
.620	.0144	.0138	.0125	.0126	.0152	.0147
.590	.0137	.0125	.0111	.0113	.0148	.0133
.570	.....	.....	.....	.....	.....	.0130
.550	.0142	.0130	.0118	.0121	.0155	.0131
.530	.0152	.0141	.0126	.0129	.0165	.0138
.500	.0178	.0166	.0150	.0156	.0209	.0163
.480	.0210	.0200	.0187	.0191	.0255	.0191
.470	.....	.....	.....	.....	.0280	.....
.460	.....	.....	.0233	.0231	.....	.023
.450	.0298	.0276	.....	.....	.0336	.0257
.440	.....	.0307	.0300	.0318	.....	.0287
.420	.0416	.0396	.0404	.0423	.0431	.0372

the reverse. However, on resuming the work after an interval of seven months, the normal had slightly raised, but came back to its original position after working for a week. In the second column of each table of data are given the readings of the normal curve against which the following reflex or fatigue curves are plotted.

Fig. 1 represents three stages in the lowering of the normal curve, the data of which are given in Table 1. The first normal plotted was that obtained after one week of steady work, the second after two weeks, and the third is the final curve which remained almost constant during the last five months. In Fig. 2 the author's final normal, marked W. A. A., is plotted with two other normals obtained by experienced

observers, who used the same apparatus and worked under the same conditions. The curve marked F. A. is Allen's normal which is almost identically the same as obtained later by M. S. Hollenberg. The third,

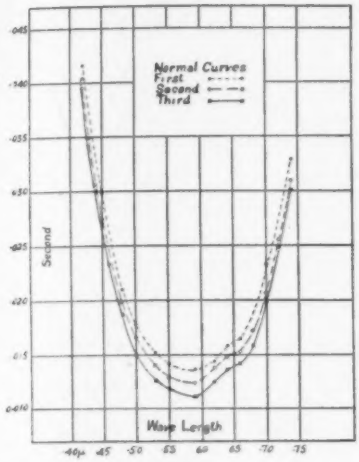

FIG. 1

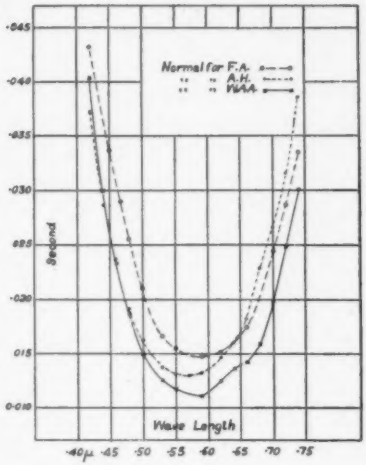

FIG. 2

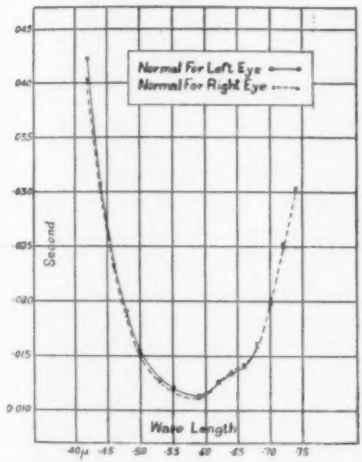

FIG. 3

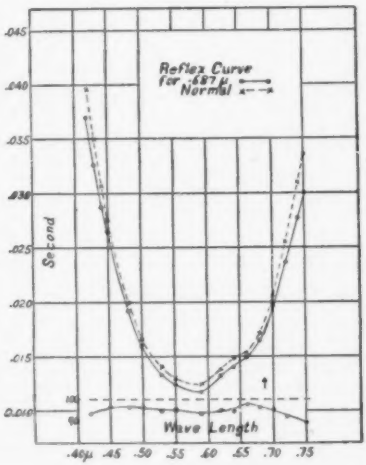

FIG. 4

marked A. H., is that of A. Hollenberg, whose color vision is noticeably deficient in the red. A comparison of the author's persistency curve

with the normal type, as obtained by Allen, indicates that the former's eye is much more sensitive to light of all wave lengths, the maximum difference being in the green and the minimum in the orange. As shown by Allen,[6] color deficiency is revealed by those portions of the persistency curve elevated above the normal type. This is well illustrated in A. Hollenberg's curve, which shows almost complete coincidence with the writer's throughout the violet and blue, but is greatly elevated, even above the normal type, in the yellow, orange and red.

At the close of the research a normal curve for the left eye was taken. This curve, plotted against the final normal for the right eye is shown in Fig. 3. It will be observed that it is of the same character as that for the right eye, the slight deviation being probably due to the fact, that the left eye was unaccustomed to taking readings. The data for all the normal curves discussed above are given in Table 1.

IV. REFLEX CURVES

All curves, plotted from results obtained by fatiguing the left eye and then making measurements on the spectrum with the right, are called reflex curves. The procedure was similar to that used to obtain a normal curve, except that the left eye was first fatigued for three minutes with the given spectral color. Care was taken in fatiguing the eye to fixate on the centre of the patch of color and to prevent the eye from wandering. The interval elapsing between the removal of the eye from the fatiguing color and the commencement of the chronographic record was from 15 to 30 seconds, while the time required to complete the record was about another 30 seconds. Since the left eye was fatigued for three minutes before every reading, and the time elapsing from one period of fatigue to the next seldom longer than a minute and a half, the eye was under almost continuous fatigue. The readings for an entire curve were usually taken at one session of two and a half to three hours. Any readings which were obviously inaccurate were repeated a few hours later, or, as was often the case, the next day. At least two or three hours, and usually one night, intervened between the taking of readings for two different fatiguing colors. In each figure two curves are plotted together to the same scale, one, the normal or reference curve, which throughout is shown as a dashed line, the second, the reflex curve, drawn as a continuous line. The coincidences and divergences of the reflex and normal curves show the effect

[6] Phys. Rev. *11*, p. 257; 1900.

of the fatiguing color in the left eye upon the physiological luminosity of the spectrum as perceived by the right.

The deviation of the reflex curve from the normal is shown in another manner, at the bottom of each figure, by giving an arbitrary value of 100 to all points in the normal curve, and reducing the reflex curve in proportion. The data for all the reflex curves are given in Tables 2, 3 and 4. The fatiguing color used is marked at the bottom of the figures by an arrow.

TABLE 2. *Reflex Curves*

λ	Normal	.687μ	.670μ	.660μ	.589μ	.570μ
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
.750μ	0.0335	0.0300	0.0308	0.0336	0.0340	0.0340
.740	.0309	.0277	.0288	.0308	.0313	.0303
.720	.0256	.0236	.0244	.0260	.0256	.0255
.700	.0206	.0197	.0201	.0208	.0205	.0216
.680	.0171	.0165	.0167	.0170	.0169	.0170
.660	.0153	.0149	.0152	.0150	.0149	.0149
.640	.0148	.0140	.0140	.0144	.0139	.0138
.620	.0138	.0132	.0131	.0132	.0129	.0130
.590	.0125	.0117	.0120	.0125	.0120	.0119
.550	.0130	.0124	.0125	.0129	.0125	.0125
.530	.0141	.0133	.0133	.0140	.0134	.0133
.500	.0166	.0160	.0166	.0165	.0165	.0166
.480	.0200	.0193	.0205	.0201	.0200	.0200
.450	.0276	.0266	.0273	.0279	.0274	.0276
.440	.0307	.0287	.0303	.0312	.0308	.0313
.430	.0350	.0327	.0352	.0369	.0346	.0354
.420	.0396	.0370	.0405	.0408	.0390	.0401

The result of fatiguing the left eye with wave length .687μ is shown in Fig. 4. The entire curve is depressed below the normal, the depressions being greatest in the two ends and middle of the spectrum, and least at the two points, about wave lengths .50μ and .66 μ, which approximate the normal curve. It is evident that the effect of fatigue on the left eye has had a reflex effect upon the right, resulting in the enhancement of the physiological brightness of the entire spectrum. Fig. 5, which shows the result when the fatiguing color was .670μ, indicates an enhancement from the extreme red to .50μ, and coincidence at .66μ and from .50μ to the violet end. When wave length .660μ was used to fatigue the eye, the reflex curve, Fig. 6, agrees closely with the normal in nearly all points, except for a slight depression in the orange, and a small elevation in the extreme violet, which may be partly due to the difficulty of making accurate measurements in this dim region of

the spectrum. It is quite probable that some color close to .660μ, such as .663μ or .665μ, might be found to give a more complete coin-

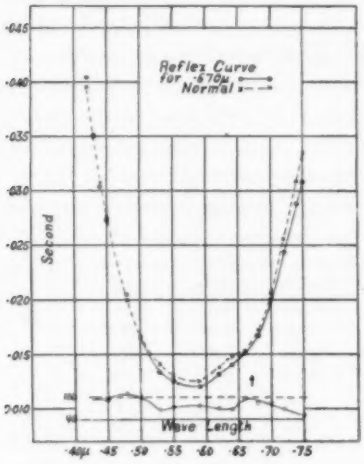

FIG. 5

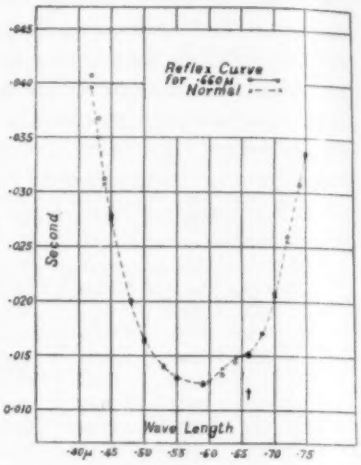

FIG. 6

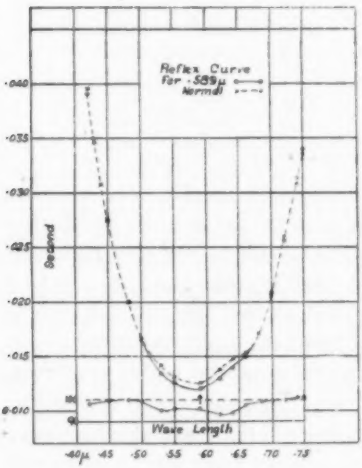

FIG. 7

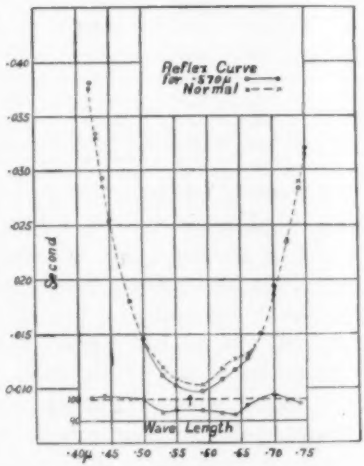

FIG. 8

cidence. Wave length .660μ is one of the equilibrium colors discovered by Allen,[7] which shows no reflex enhancement in the other eye.

[7] Phil. Mag. *38*, p. 55; 1919. Also J. O. S. A. *7*, p. 583; 1923.

The reflex curve for a fatiguing color of .589μ, Fig. 7, shows a further reduction in the extent of reflex enhancement, as compared with Figs. 4 and 5. The enhanced effect is confined to the middle part of the spectrum between wave lengths .50μ and .66μ, while the remainder of the curve coincides with the normal. The transferred reflex enhancement for fatigue color .570μ, as shown in Fig. 8, is very similar to that for .589μ, except that the amount of enhancement in the orange is a little greater. Since wave length, .570μ, another of the equilibrium colors discovered by Allen, did not give the same result for the writer, another color near to it was tried, namely, .565μ. This proved to be an almost

TABLE 3. *Reflex Curves*

λ	Normal	.565μ	.535μ	.520μ	.410μ
	Sec.	Sec.	Sec.	Sec.	Sec.
.740μ	0.0293	0.0291	0.0265	0.0296	0.0256
.720	.0234	.023.	.0222	.0238	.0212
.700	.0190	.0188	.0181	.0199	.0174
.680	.0162	.0160	.0155	.0163	.0150
.660	.0142	.0143	.0142	.0141	.0138
.640	.0136	.0136	.0135	.0134	.0129
.620	.0127	.0126	.0128	.012	.0116
.590	.0113	.0113	.0109	.0114	.0108
.550	.0120	.0120	.0116	.0120	.0111
.530	.0127	.0129	.0125	.0129	.0120
.500	.0151	.0150	.0152	.0152	.0151
.480	.0178	.0175	.0177	.0180	.0180
.460	.0224	.0223	.0228	.0225	.0208
.440	.0299	.0297	.0306	.0302	.0266
.420	.0383	.0376	.0376	.0389	.0366

perfect equilibrium color, as shown in Fig. 9. The reflex curve for .535μ, as plotted in Fig. 10, shows, like some of the previous curves, an enhancement in the red and yellow-green, and coincidence with the normal from .50μ to the end of the violet. It differs from the other reflex curves by showing coincidence in the region corresponding to the abnormal part of the reference curve, which, however, includes .66μ.

All fatigue colors chosen from the spectrum between wave lengths .520μ and .480μ resulted in giving good equilibrium curves very similar to Fig. 9. Curves for the following wave lengths were obtained, .520μ, .513μ, .505μ, .495μ, and .480μ, the data for which are given in Tables 3 and 4, but the curves themselves are not reproduced in this paper since they resemble closely Fig. 9. In this part of the spectrum Allen found three equilibrium colors, .520μ, .505μ and .480μ, while

wave lengths .513μ and .495μ gave small reflex enhancements. Since most of the transferred reflex effects obtained by the writer are smaller than those shown by Allen's curves, it is quite probable that, if any

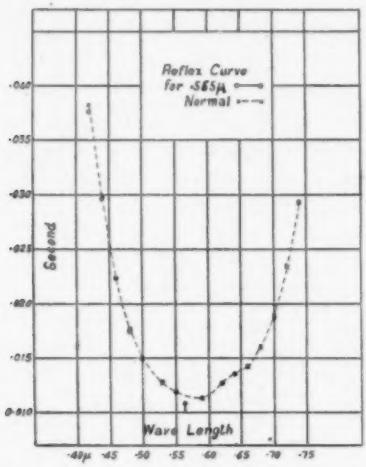

FIG. 9

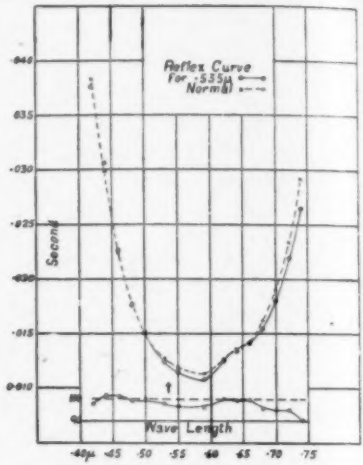

FIG. 10

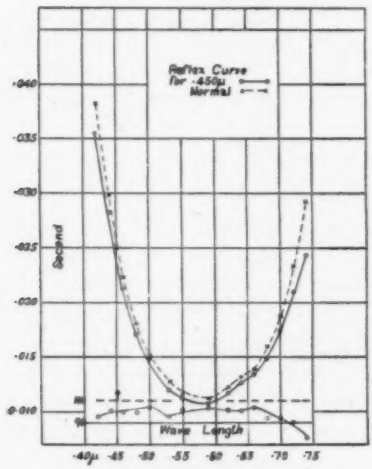

FIG. 11

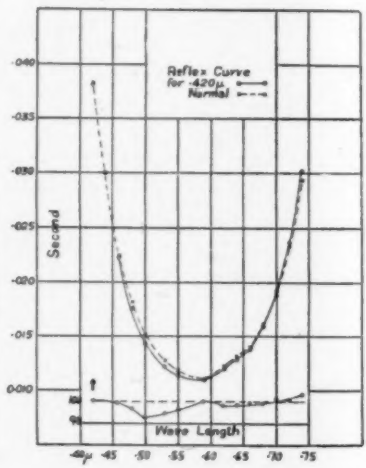

FIG. 12

reflex action is produced by either .513μ or .495μ in the writer's eye, it is too small to be detected.

The reflex curve for wave length .450μ as shown in Fig. 11, reveals a decided enhancement throughout the entire spectrum. The effect is most pronounced in the red, and least again about .50μ and .66μ. It may be observed that most of the reflex curves tend to coincide with the normal at these two points, which Allen has called "coincidence points." When wave length .420μ was used to fatigue the eye a small reflex enhancement was obtained, as shown in Fig. 12, but when .425μ was tried the reflex curve coincided throughout with the normal, thus giving the same equilibrium color as found by Allen.

TABLE 4. *Reflex Curves*

λ	Normal	.513μ	.505μ	.495μ	.480μ	.450μ	.425μ	.420μ
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
.740μ	0.0293	0.0287	0.0290	0.0293	0.0290	0.0243	0.0293	0.0303
.720	.0234	.0231	.0231	.0233	.0236	.0210	.0231	.0237
.700	.0189	.0188	.0189	.0189	.0187	.0174	.0189	.0193
.680	.0161	.0157	.0160	.0158	.0158	.0148	.0160	.0159
.660	.0138	.0137	.0141	.0138	.0138	.0134	.0138	.0140
.640	.0131	.0131	.0133	.0128	.0132	.0126	.0132	.0128
.620	.0122	.0121	.0122	.0120	.0124	.0117	.0124	.0120
.590	.0111	.0114	.0110	.0112	.0112	.0108	.0113	.0111
.550	.0118	.0118	.0117	.0118	.0118	.0113	.0120	.0114
.530	.0128	.0128	.0125	.0126	.0126	.0119	.0127	.0122
.500	.0152	.0153	.0150	.0152	.0148	.0148	.0153	.0142
.480	.0181	.0182	.0178	.0185	.0179	.0171	.0183	.0175
.460	.0224	.0225	.0222	.0229	.0228 •	.0213	.0222	.0223
.440	.0299	.0295	.0301	.0301	.0303	.0283	.0294	.....
.420	.0383	.0385	.0386	.0389	.0383	.0355	.0389	.0385

Although the luminosity of the violet fatiguing color was comparatively low, yet the largest reflex effects were obtained for the fatigue colors .450μ and .410μ. The results of the latter are shown in Fig. 13. Like .450μ, it produced a large enhancement throughout the entire spectrum except at the coincidence points .50μ and .66μ.

An examination of the reflex curves as a whole shows a very interesting fact, namely, that the largest reflex enhancements are not obtained by fatiguing with the brightest colors, but rather with the dim colors, such as .687μ, .450μ and .410μ. These wave lengths stimulate predominantly one sensation each; the first is confined almost entirely to the red sensation, while the latter two affect chiefly the violet. It would appear, therefore, that the large enhancements, obtained by fatiguing with the above colors, is due, either to their lower luminosity, or to the simplicity of their stimulations of the fundamental sensations.

A comparison of the various reflex curves shows that a reflex enhancement in the violet is obtained only when the fatiguing color is one of comparatively low luminosity, such as a red or violet. When a reflex does occur it is always manifested in the most luminous portion of the spectrum, and with the exception of the reflex curve for .589μ, also in the red. It was therefore of interest to determine the reflex effect of an intense white light.

The left eye was fatigued with a similar patch of white light, obtained by removing the prisms from a spectrometer and viewing the white light in the eyepiece. By this means, the area of the retina stimulated was the same as for the other fatigue colors. The results, as shown in Fig. 14, are similar to those obtained for bright colors throughout the middle of the spectrum. The curve from .48μ to the violet end coincides almost completely with the normal, while the remainder, with the exception of about .68μ, shows a distinct reflex enhancement. The data for this curve and the next are given in Table 8.

Before taking any readings for the reflex effect of darkness adaptation in one eye upon the perception of the luminosity of colors by the other, the left eye was blindfolded for about an hour, and kept in that state until all the observations, which were taken at the rate of one every five minutes, were completed. This curve, as plotted in Fig. 15, is quite different from any of the other reflex curves in that the entire curve, with the exception of the abnormal region .59μ to .66μ, is elevated above the normal. This clearly verifies the observations made by Allen, that dark adaptation in one eye lowers the physiological luminosities of colors perceived in the other, a fact, which shows the importance of investigating reflex phenomena in daylight, when the unused eye is under natural light adaptation.

The majority of the reduced curves, shown at the bottom of the figures, indicate a division into three parts, two of which correspond to the sensations of red and violet, while the third is in the middle portion of the spectrum, where green may be considered as the predominant sensation stimulated.

These curves fully verify the principle discovered by Allen, that the effect of fatigue, by a light stimulus in one eye, is transferred to the other by a reciprocal or reflex action of some kind, resulting in an enhancement of the physiological luminosity of the spectral colors perceived by the unfatigued eye. They differ from his in that the amount of enhancement is generally less, being sometimes very slight

or even absent, especially in the blue and violet, or that part which stimulates chiefly the violet sensation. The wave lengths of the equilibrium colors are approximately the same as found by Allen,

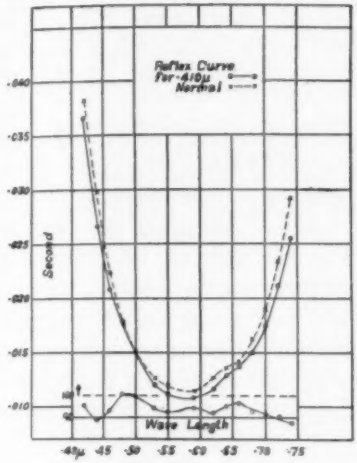

FIG. 13

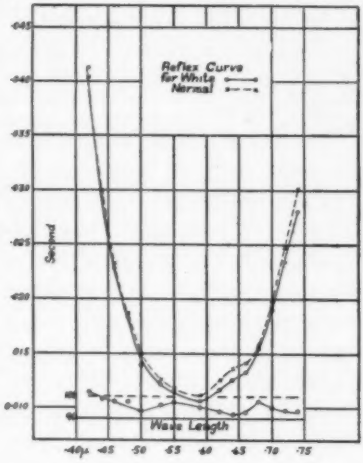

FIG. 14

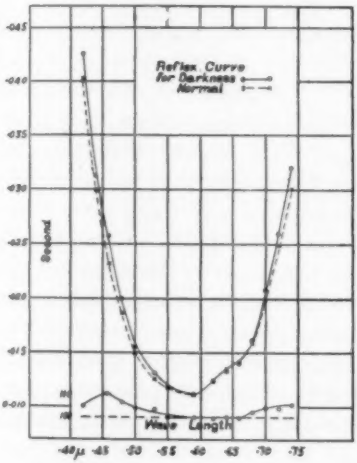

FIG. 15

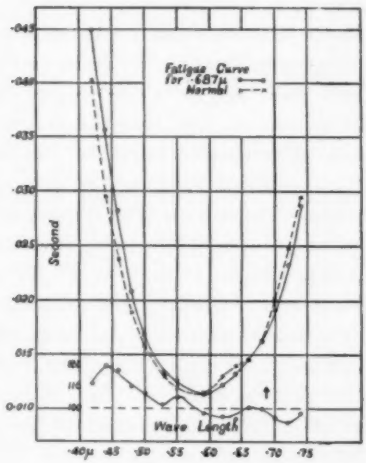

FIG. 16

except for the additional colors between .520μ and .480μ, which also gave very good equilibrium curves. The two coincidence points, .50μ and .66μ, also agree well with his.

V. FATIGUE CURVES

In this part of the investigations both the direct and reflex effects of fatigue in the same eye were studied. The same procedure was followed as for the reflex curves, except that the right eye was now fatigued and the measurements made on the same eye, while the left was maintained in daylight adaptation. The data for the fatigue curves are given in Tables 5, 6 and 7.

The first color used to fatigue the eye was wave length .687μ, obtained from the arc light by means of a two prism Browning spectrometer. The results obtained were entirely unexpected, and it was thought that some error must have been made, either in recording the measurements, or in the use of the spectrometer providing the fatiguing color. Another spectrometer was taken and carefully recalibrated, and the curve repeated twice with the greatest care to get correct readings, first, using the arc spectrum to provide the fatiguing red, and second, an incandescent bulb. All three curves were identically of the same character, showing only small variations in the amount by which they deviated from the normal. One of the curves is shown in Fig. 16. Instead of getting an elevation in the red indicating fatigue, as was expected, a distinct depression was the result. The curve, after touching the normal at the coincidence point, about .66μ, again shows another depression through the abnormal region. At .59μ it crosses the normal and gives an elevation throughout the remainder of the spectrum. It is to be noticed, that this is the first curve obtained showing smoothness throughout the region .59μ to .66μ. It is evident, therefore, that the combined result of the direct and reflex effects of fatiguing with .687μ, is to enhance the physiological luminosity of those parts of the observed spectrum corresponding to the depressions of the fatigue curve, and to decrease it for the parts showing an elevation. While measurements were being made on that part of the spectrum from .62μ to .74μ, it was observed that the red appeared less saturated but brighter. The yellow appeared greenish, and the colors from .55μ to the violet end duller. The effect of fatigue began to pass off rapidly at the end of about one minute, as observed by the return of the natural appearance of the spectrum.

Fatiguing with .670μ, Fig. 17, resulted in giving a curve very similar to the previous one, except that the deviations from the normal are more pronounced, especially the enhancement corresponding to the abnormal region of the reference curve. The effects of fatigue did not pass off

nearly as rapidly as for .687μ. It has expected that the fatigue curve for .660μ would probably show almost complete coincidence with the normal, as was obtained for the reflex curve. Instead, however, as shown in Fig. 18, the curve is similar to the previous two, showing even a greater enhancement in red and also a greater fatigue in the yellow and green. The two coincidence points .50μ and .66μ are well marked. This curve was also repeated on another day after having carefully checked the normal, as was always done every few days. The results fully verified the first curve.

The three fatigue curves, now described for different wave lengths of red, show largest enhancements in regions about .72μ and .64μ, and greatest fatigue about .44μ. In an attempt to locate, if possible, an

TABLE 5. *Fatigue Curves*

λ	Normal	.687μ	.670μ	.665μ	.660μ
	Sec.	Sec.	Sec.	Sec.	Sec.
.740μ	0.0295	0.0288	0.0287	0.0293	0.0280
.720	.0248	.0232	.0229	.0248	.0218
.700	.0202	.0193	.0191	.0194	.0190
.680	.0163	.0163	.0163	.0165	.0168
.660	.0146	.0147	.0142	.0147	.0144
.640	.0140	.0133	.0130	.0137	.0132
.620	.0130	.0122	.0118	.0128	.0124
.590	.0115	.0113	.0112	.0115	.0120
.550	.0120	.0126	.0119	.0122	.0127
.530	.0131	.0134	.0136	.0132	.0138
.500	.0158	.0169	.0168	.0158	.0162
.480	.0189	.0209	.0218	.0197	.0200
.460	.0238	.0282	.0279	.0236	.0286
.440	.0295	.0356	.0355	.0295	.0344
.420	.0403	.0450	.0509	.0410	.0435

equilibrium color in the region of .660μ, wave length .665μ was tried as a fatiguing color, with the result that both curves show very good coincidence throughout the entire spectrum, as shown by the data in Table 5. A distinct difference in the effects of fatigue by .665μ and .660μ could be noticed on the red end of the spectrum, the former causing but little change in either saturation or apparent brightness, while the latter caused the red to appear noticeably less saturated but brighter.

It was of interest to determine the effect of fatiguing the eye with a color selected from that part of the spectrum, which gives the abnormal elevation in the reference curve. Wave length, .630μ was selected and

a fatigue curve obtained for it, the character of which is shown in Fig. 19. Like the other fatigue curves for red, a smooth curve was obtained without any trace of an irregular elevation between .59μ and .66μ.

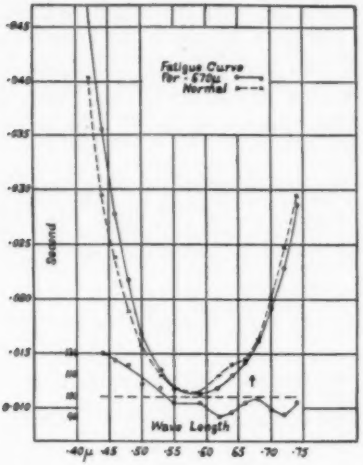

FIG. 17

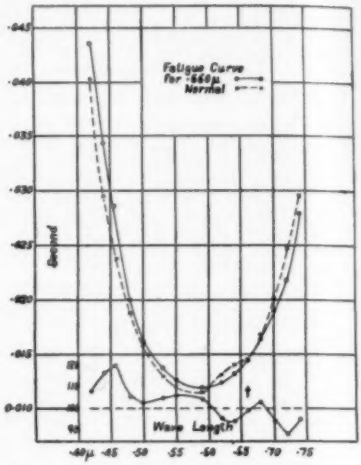

FIG. 18

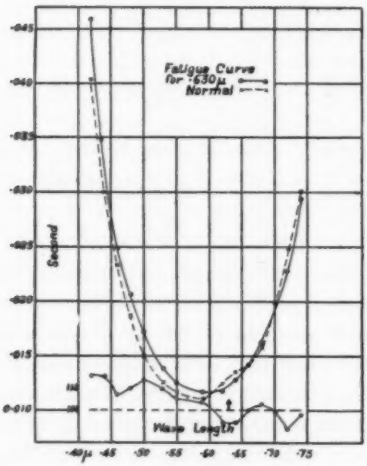

FIG. 19

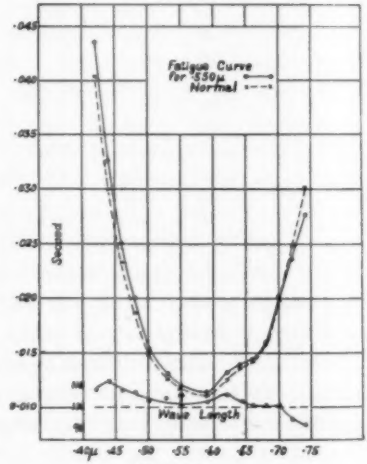

FIG. 20

As has been observed, the curves for wave lengths .687μ and .670μ both of which are on the same side of the equilibrium color, .665μ, are very similar; so, too, the curves for .660μ, and .630μ, on the other side

of .665μ, show close resemblances. Wave length .630μ shows smaller enhancement in the red, but much larger fatigue in the green. The disproportionately large enhancement occurring about .72μ, as also referred to in the previous figures, is a noticeable feature. The observations on this point were repeated for nearly all the red fatigue curves, but in every case, the new readings confirmed the original.

When .589μ, the brightest color in the spectrum, was employed to fatigue the eye, another surprising result was obtained. As shown by the data in Table 6, the readings are almost identical with those for the normal curve, .72μ being the only point to show any appreciable variation, and this in the nature of a slight enhancement. For the

TABLE 6. *Fatigue Curves*

λ	Normal	.630μ	.570μ	.550μ	.535μ	.520μ	.589μ
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
.740μ	0.0301	0.0295	0.0303	0.0277	0.0283	0.0303	0.0298
.720	.0249	.0228	.0242	.0236	.0238	.0240	.0239
.700	.0199	.0198	.0193	.0202	.0208	.0195	.0201
.680	.0158	.0163	.0155	.0160	.0170	.0158	.0160
.660	.0142	.0142	.0141	.0144	.0145	.0144	.0143
.640	.0136	.0128	.0133	.0140	.0141	.0134	.0136
.620	.0125	.0118	.0124	.0132	.0134	.0124	.0124
.590	.0111	.0117	.0112	.0114	.0114	.0115	.0110
.550	.0118	.0125	.0117	.0120	.0120	.0124	.0115
.530	.0126	.0139	.0123	.0131	.0129	.0128	.0125
.500	.0150	.0172	.0157	.0154	.0162	.0153	.0156
.480	.0187	.0206	.0187	.0201	.0201	.0183	.0187
.460	.0233	.0249	.0236	.0251	.0249	.0242	.0237
.440	.0300	.0348	.0297	.0236	.0294	.0316	.0305
.420	.0404	.0469	.0414	.0435	.0390	.0412	.0407

writer's eye, therefore, wave length .589μ is an equilibrium color, when measurements are made on the fatigued eye. It may be recalled, that even the reflex curve for .589μ, Fig. 7, coincided with the normal except in the middle part of the spectrum from about .53μ to .66μ. The fatigue equilibrium color, corresponding to .565μ of the reflex curves, was found when .570μ was employed. As shown by the data in Table 6, a very good agreement exists between the normal and most of the fatigue readings.

The fatigue curves for wave lengths .550μ and .535μ are quite similar, as shown in Figs. 20 and 21. Both show an enhancement in the extreme red, fatigue in the yellow, orange and orange-red, very little change in the green, but considerable fatigue in the blue. In the violet

there is a difference, one showing distinct fatigue, the other coincidence except for a slight enhancement in the last point.

Fig. 22 shows the curve for fatigue color .520μ, which, although not quite an equilibrium color, yet suggests that a slightly shorter or longer wave length would result in such. When making observations for the reflex curves, all colors between .520μ and .480μ showed no change in the persistency curve, but when these same colors were employed to obtain fatigue curves none were found to give equilibrium effects. Figs. 23, 24 and 25, show the curves for the fatigue colors, .513μ, .505μ and .480μ respectively. All three curves are somewhat similar, showing fatigue to a greater or less degree in all parts, except in the extreme red and violet. Wave length .513μ, however, indicates also a fatigue of the extreme violet. According to the intersections of the equal area sensation curves of König and Dieterici,[8] this portion of the spectrum is quite complex and it is, therefore, not surprising that almost all parts of the spectrum should show fatigue. On the other hand, the largest reflex effects in the unfatigued eye were obtained for the comparatively pure colors, red and violet, which arouse predominantly one sensation each and but slightly the other two. Since white light, and most colors stimulating the three sensations to a considerable degree, produce comparatively small reflex results, it is not surprising that the above mentioned complex region of the spectrum should give equilibrium reflex curves.

The fatigue curves for wave lengths .450μ and .425μ, Figs. 26 and 27, show fatigue in all parts of the spectrum, the former, except in the extreme red, to a much more marked degree. It may be observed from these two curves, and also from .480μ, that greatest fatigue is shown in that part of the spectrum corresponding to the fatiguing color. When the dim violet, .410μ, was employed, the fatigue was only evident in the less bright parts of the spectrum, as shown in Fig. 28. It is possible, that the considerably brighter region of the spectrum, from .50μ to .66μ, rapidly overcame the state of fatigue due to the dim violet. It is also possible, that the eye was under partial darkness adaptation, due to the comparative darkness of the spectrometer tube, in the centre of which, the dim violet was fixated for three minutes out of every four. This latter possibility seems the more probable in view of the effect of darkness adaptation on the same eye with which the measurements are made. This effect is shown in the next curve.

[8] Parsons: "Colour Vision" p. 222.

Before taking any readings for the fatigue curve for darkness, as it may be called since the results are similar to fatigue, the right eye was bilndfolded for about one hour. Readings were made on the spectrum,

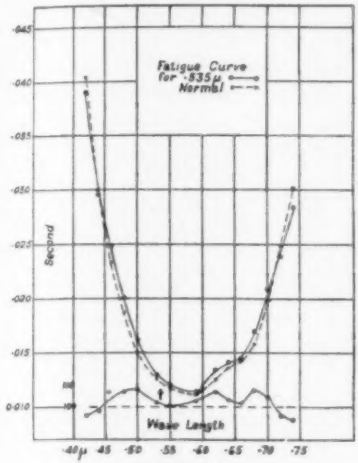

FIG. 21

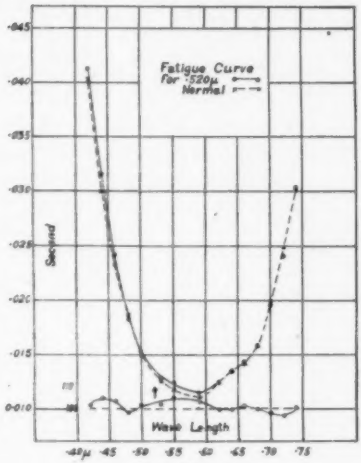

FIG. 22

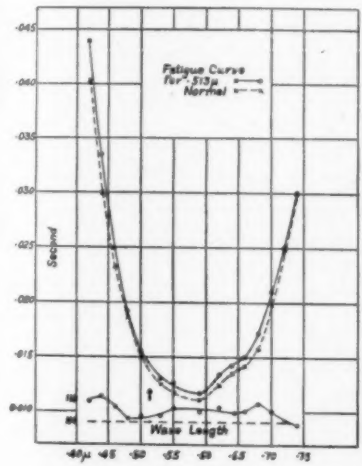

FIG. 23

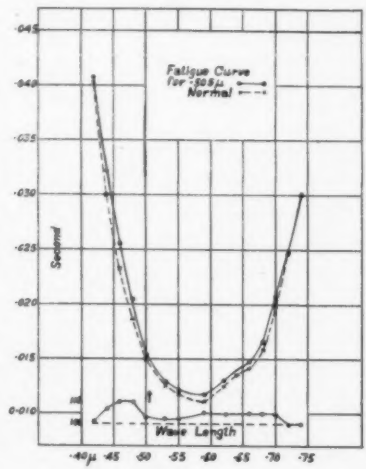

FIG. 24

still in the daylight room, by uncovering the eye for the brief period of about thirty seconds which was required to make the chronographic record. While uncovering the eye and placing it in the shield attached

to the spectrometer eye piece, care was taken to prevent any daylight from entering the eye. Between readings the eye was kept blindfolded for five minutes. Although the appearance of the spectrum to the dark adapted eye was such as to suggest an increase in the brightness, yet the true effect must be judged by the actual measurements obtained. These measurements, as plotted in Fig. 29, clearly show that the effect of darkness adaptation is to lower the physiological luminosity of the spectrum, a fact, which was pointed out by Allen[9] over twenty years ago. The effect, as obtained by the writer, is not marked in the most luminous part of the spectrum. This may be caused by the rapid disappearance of the effects of darkness adaptation in the presence of

TABLE 7. *Fatigue Curves*

λ	Normal	.513μ	.505μ	.480μ	.450μ	.425μ	.410μ
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
.740μ	0.0301	0.0299	0.0300	0.0292	0.0305	0.0313	0.0320
.720	.0249	.0250	.0248	.0257	.0258	.0259	.0264
.700	.0199	.0210	.0208	.0210	.0222	.0217	.0220
.680	.0158	.0172	.0166	.0173	.0177	.0174	.0168
.660	.0142	.0150	.0148	.0151	.0150	.0150	.0144
.640	.0136	.0142	.0136	.0140	.0145	.0140	.0138
.620	.0125	.0134	.0130	.0136	.0134	.0134	.0129
.590	.0111	.0117	.0117	.0119	.0121	.0115	.0110
.550	.0118	.0126	.0121	.0126	.0128	.0123	.0117
.530	.0126	.0130	.0129	.0137	.0133	.0133	.0124
.500	.0150	.0155	.0154	.0176	.0171	.0162	.0152
.480	.0187	.0192	.0205	.0213	.0220	.0208	.0195
.460	.0233	.0250	.0256	.0248	.0280	.0262	.0252
.440	.0300	.0335	.0322	.0314	.0349	.0336	.0322
.420	.0404	.0440	.0408	.0400	.0427	.0457	.0417

the comparatively bright spectral colors, upon which the measurements were being made; for it has already been pointed out, that the author's eye is much more sensitive than normal to a light stimulus.

To obtain a fatigue curve for white light, the eye was fatigued by a moderately bright light, transmitted through a spectrometer with the prisms removed, as was the case for the reflex curve. A very brilliant light made it almost impossible to get consistent readings because of the vivid after images produced. The readings from which Fig. 30 was plotted showed, however, good agreement. The character of this curve is interesting in the relation which it bears to all the other fatigue curves. This curve is really the combined effect of the main

[9] Phys. Rev. *11*, p. 265; 1900.

types of fatigue curves, for it reveals a large fatigue in the yellow, green, blue and violet colors, as is also shown to a greater or less extent by nearly all the fatigue curves, but shows little or no fatigue in the red

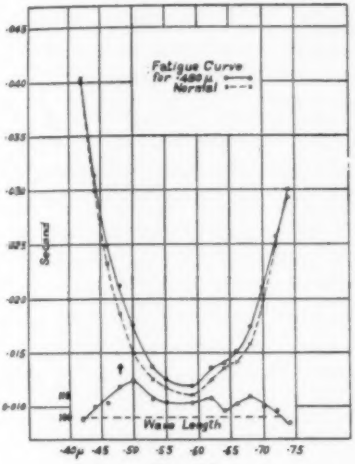

FIG. 25

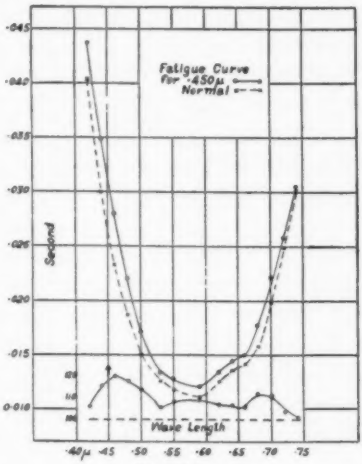

FIG. 26

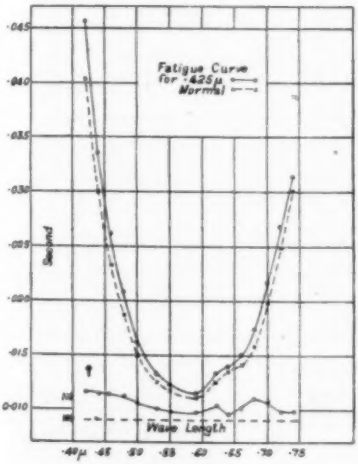

FIG. 27

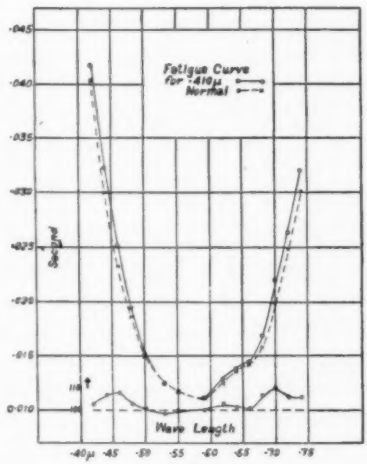

FIG. 28

end of the spectrum, a result which is about the average effect for all the fatigue colors. The data for the two curves on white light and darkness are given in Table 8.

A general survey of all the fatigue curves, except those for equilibrium colors, reveals three fairly distinct types, which change more or less gradually from one type to the other. When the fatiguing color is any

TABLE 8. *Light and Darkness Curves*

λ	Normal	Reflex Darkness	Fatigue Darkness	Reflex White	Fatigue White
.740μ	0.0301	0.0320	0.0323	0.0281	0.0301
.720	.0249	.0260	.0259	.0234	.0257
.700	.0199	.0208	.0220	.0190	.0197
.680	.0158	.0162	.0165	.0155	.0162
.660	.0142	.0139	.0148	.0132	.0148
.640	.0136	.0133	.0140	.0125	.0137
.620	.0125	.0125	.0127	.0116	.0128
.590	.0111	.0110	.0110	.0106	.0120
.550	.0118	.0118	.0115	.0115	.0128
.530	.0126	.0131	.0128	.0121	.0138
.500	.0150	.0156	.0157	.0139	.0165
.480	.0187	.0201	.0198	.0183	.0205
.460	.0233	.0259	.0260	.0228	.0260
.440	.0300	.0312	.0340	.0298	.0339
.420	.0404	.0426	.0462	.0413	.0459

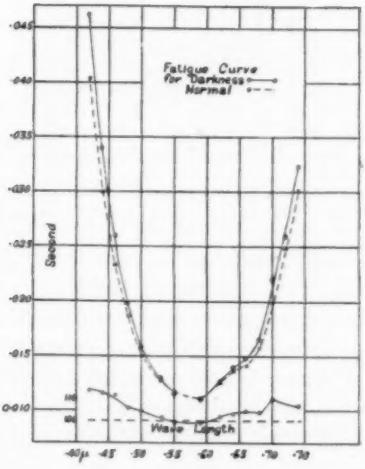

FIG. 29

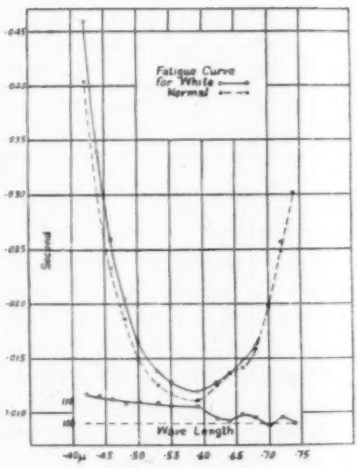

FIG. 30

hue of red, there is always an enhancement in the extreme red and orange-red, the amount of which is less for the fatigue color, .630μ than for those of longer wave length. The depression in the brightness of

the green region of the spectrum increases in amount with a decrease in the wave length of the red fatiguing color, while the violet end shows always a distinct lowering of the physiological luminosity. The equilibrium curves for yellow fatiguing colors separate the red type from the green, or second type. Fatiguing with green gives an enhancement in the red, the amount of which decreases as the fatigue color moves towards the blue, the blue showing little or no effect on the longer red waves; on the orange-red the effect is a lowering of the brightness, the amount of which increases with a decrease in the wave length of the fatigue color. Green fatigue curves also show a depression in the brightness of the green, blue and violet colors, the amount of which increases as the fatigue color becomes more blue.

The second type changes gradually through the fatigue curves for blue to the third type, which is for violet fatiguing colors. The transition curves in the blue show but little fatigue or enhancement for the extreme red or violet, and an increasing fatigue in the brighter colors. The violet curves give a depression in luminosity throughout the entire spectrum, the amount of which decreases as the fatiguing color approaches the extreme end of the spectrum, until for .410μ the brighter part of the spectrum shows no change.

The reduced curves at the bottom of the figures show a tendency to divide, in most cases, into three regions, which are not regular enough in all the curves to say that they indicate always the three fundamental sensations, red, green and violet. The existence of these three fundamental sensations is indicated more particularly by the natural division of the curves into the three main types as already described.

VI. THEORETICAL CONSIDERATIONS

The experimental results, which have now been considered, fully verify Allen's discovery of the dual action of light in arousing visual sensations. Although the character of many of the curves, given in this paper, differ considerably from his, yet they clearly show that in addition to the direct effect of light, which tends to produce fatigue, there is also a reflex effect, resulting in an enhancement of the fundamental sensations. Several of the reflex curves are very similar to Allen's, showing that, when a light stimulus falls upon one eye, the sensory reflex is transferred to the other causing an enhancement of all three sensations. Certain colors, which are termed equilibrium colors, apparently produce no effect in the physiological brightness of the

colors perceived by the unfatigued eye, while fatigue by still different wave lengths enhances only the red and green sensations in the opposite eye and not the violet. The violet sensation in the writer's eye seems the least sensitive to stimulation by a sensory reflex, transferred from one eye to the other.

In the same eye, Allen found that the direct effect of a color stimulus was to cause a diminution in the physiological brightness of the colors, corresponding to the primary color sensations represented in the fatiguing color, and that the reflex effect was to enhance the brightness of those colors which stimulate chiefly the complementary sensations.

The majority of the author's fatigue curves, however, are quite different from those obtained by Allen. When red of any wave length, except .665μ, was employed as the fatiguing color, the result was not a diminution in the brightness of the red, observed in the other spectrometer, and a corresponding enhancement of those colors representing predominantly the green and violet sensations. Instead, the red sensation was actually enhanced, the violet fatigued, and the green little affected, except by the shorter red waves which fatigued it. Stimulation with green shows fatigue in the green and violet and enhancement in the red, but violet, however, fatigues more or less all three sensations.

Although these results are not of the normal type, yet it is evident that the conclusions drawn from Allen's researches do not give a complete statement of the direct and reflex stimulation of the fundamental color sensations when light falls upon the retina. A more comprehensive statement, which is based on the results shown by the curves in this paper, may be expressed as follows:

Light of every hue falling upon the retina affects all three sensations both directly and reflexly. For example, a green light stimulates by direct action all three sensations, but predominantly the green, and by reflex action also the three sensations, but predominantly the red and violet. The direct effect always tends to produce fatigue, and the reflex, enhancement. In normal vision under ordinary conditions, if we again take green as the fatiguing color, the direct effect on the green sensation overbalances the reflex action on the same sensation, resulting in a fatigue of the green sensation; and the reflex effect on the complementary sensations, red and violet, overbalances the direct effect on the same sensations, thus producing enhancement of the complementary sensations. While the eye is still being stimulated by the green light, the direct effect usually predominates over the reflex, the net

result being a sensation of green with an underlying whiteness, which increases with fatigue. However, under certain conditions, and especially in cases of abnormal vision, the above is not always the net result of direct and reflex stimulation of the sensations. The discussion of this point, however, will be postponed until after the author's type of abnormal vision has been considered.

Helmholtz suggested that every ray in the spectrum affected each of the three sensations, red, green and blue. Abney in referring to Helmholtz's suggestion states,[10] "If Helmholtz's diagram, p. 214, were correct, one colour would never stimulate one sensation by itself. As it is, however, the red stimulates only the red sensation in one part of the spectrum, whilst the violet stimulates both the red and the blue, and not the green sensations. A green color stimulates not only the green sensation, but it stimulates the red and blue as well, as is shown in Helmholtz's diagram. The trichromatic theory requires this to be the case." The experimental results given in this paper show that Helmholtz was right in his assumptions, although unaware that the three fundamental color sensations are stimulated reflexly as well as directly by every hue. Abney failed to detect the dual nature of the action of light upon the retina, partly, no doubt, because of the negative effect of darkness adaptation, and partly because many of his observations were based on the assumption that light falling upon one eye has no effect upon the other, a conclusion which these researches show to be incorrect.

ANOMALOUS TRICHROMATISM

The author has no difficulty whatever in passing ordinary wool and card tests for color deficiency, nor has he, at any time, experienced any phenomena apart from these experiments to indicate that his vision is in any way abnormal. Slight pleochroism in certain minerals under the polarising microscope can be observed, even when the effect is too weak to be detected by as many as one quarter of a class. There is also no shortening of the spectrum at either end, as compared with those whose color vision is undoubtedly normal. However, a comparison of the author's normal persistency curve, and especially his fatigue curves, with those obtained by Allen, indicates that an abnormality of some sort certainly exists. Allen's curves have been fully confirmed by M. S. Hollenberg,[11] who not only obtained the same normal curve,

[10] "Researches in Color Vision," p. 230.

[11] J. O. S. A. & R. S. I., *8*; p. 713, 1924.

but also the same type of reflex and fatigue curves. Their results appear therefore, as those of observers whose color vision is in every way normal.

A comparison of the author's normal curve with that of Allen, Fig. 2, shows that the greatest deviation is in the green and yellow, or that part which corresponds predominantly to the green sensation, and the least departure from the normal type in the orange and orange-red, from .59μ to .66μ. An examination of the sensation curves of König and Dieterici,[12] shows that the green sensation falls to zero in this region. Although, in light of the principle of reflex stimulation of sensations, all three sensation curves should extend to the ends of the visible spectrum, yet the above mentioned curves are no doubt correct in indicating that, at least, the direct stimulation of green beyond .66μ is very small. The elevation in the author's normal curve between .59μ and .66μ would appear, therefore, to be due to a deviation of the green sensation curve, rather than the red, from that of the normal type. It seems probable that, if the writer's sensation curves were determined and plotted as equal area curves after the manner of those of König and Dieterici, the green sensation curve would be found to show a depression, as compared with the normal type, for the region between .59μ and .66μ, and a corresponding elevation throughout the yellow and green parts of the spectrum.

It is well known that there are individuals, who show no color deficiency whatever, but who, in matching a spectral color, by two mixed colors, differ in their equation from that of the normal. For example, when making the equation, .670μ+.535μ=.589μ, some require more red and others more green than the normal. Those requiring more red are commonly called red anomalies, and those requiring more green, green anomalies. Edridge-Green states,[13] "There are also those who will make normal equations when the red employed is λ670, but will make an anomalous equation with a red of larger wave length, as for instance λ690, putting in twice as much red in the mixture compared with the normal equation in similar circumstances." It is quite conceivable that an individual, who is not color deficient, may not only agree with the normal in the equation, .670μ+.535μ=.589μ, but also with a few other equations, and yet differ from the normal when still different wave lengths are employed. Such individuals must be classed as anomalous trichromats.

[12] Parsons: "Colour Vision," p. 222.
[13] "Physiology of Vision," p. 223.

As the results of the experiments, given in this paper, were studied more closely it became more convincing that their abnormal characters must be due to anomalous trichromatism. It therefore became desirable to test the author's color vision by means of color equations.

The apparatus used was Allen's trichromatic spectrometer,[14] in which two colors can be isolated and mixed in the upper part of the shutter eyepiece, and a single color in the lower part. Each of the three colors were obtained from the separate spectra of three acetylene flames of constant luminosity. The intensity of a color was altered by opening or closing the collimator slit.

The first equation attempted was $.670\mu + .535\mu = .589\mu$, but in this the author agreed with the normal equation as obtained by Allen and others. It will be noticed by reference to the normal curve, Fig. 2, that these three wave lengths are outside of the writer's particularly abnormal region, $.59\mu$ to $.66\mu$. The red was then changed to a longer wave length $.690\mu$, but again the difference was not sufficient to say that an actual disagreement existed. The same was true when a longer wave length of $.720\mu$ was used instead of $.690\mu$. The next step was to select a wave length from the abnormal region, $.59\mu$ to $.66\mu$, as one of the three colors. The first equation made was $.670\mu + .535\mu = .630\mu$. In this case, when the match was perfect for the normal eye, it appeared distinctly too yellow to the writer, and the amount of green had to be decreased to give a good match. When the red was changed to $.690\mu$ and $.720\mu$ the same results were obtained.

Wave length $.630\mu$ affects chiefly the red and green sensations; and since a less amount of green, or a greater amount of red, is required than normal to match $.630\mu$, it is evident, that either the green sensation is comparatively less stimulated, or the red more stimulated than normal by colors between $.59\mu$ and $.66\mu$. A comparison of the writer's normal persistency curve with that of a normal trichromat, as has already been pointed out, would indicate that the abnormalty is due to an over sensitiveness of the green sensation to wave lengths of the yellow and green regions of the spectrum, and to an under sensitiveness of the same sensation to wave lengths between $.59\mu$ and $.66\mu$. In this respect, therefore, the author is an anomalous trichromat, but according to the general distinction between green and red anomalies he would be classed as a red anomaly, since he requires more red in the equations than the normal.

[14] J. O. S. A. & R. S. I., *8*, p. 339; 1924.

Anomalous trichromatism, and in fact color vision in any phase, cannot be studied fully unless both the direct and reflex action of a light stimulus on the retina be taken into consideration. Heretofore, only the direct effect of light was considered, and that not generally to the extent that every ray affects, to a greater or less extent, all three sensations. An individual may be not only anomalous in respect of the direct effect of light, but also anomalous in the development of his reflex sensations. The latter phase is probably most easily detected after prolonged stimulation, since the reflex sensation, which may be set up in a very small fraction of a second, increases with continued stimulation.

While fatiguing the eye with a brilliant green light it was observed that, at the end of about 25 seconds, the light began to lose its green color and to assume a purple tinge, which increased in saturation for another 25 seconds, at the end of which the color appeared more purple than green; the purple then gradually decreased until, at the end of about 90 seconds, it again appeared a dull green of much reduced intensity and saturation. A similar effect was observed when fatiguing with a strong white light. The white light became distinctly pink, which gradually increased for a short time and then slowly disappeared as the fatigue reached a maximum. However, when using a brilliant red light no tinge of green could be observed although at first it was expected. These observations may be readily explained as follows:—

An examination of the fatigue curves shows that the author's violet sensation is easily fatigued by nearly all hues to a greater or less extent. From the reflex curves, it may also be seen, that violet perceived by the other eye is not markedly enhanced by a transferred reflex stimulation, except when the fatiguing color is near either end of the spectrum. It therefore appears, that with prolonged stimulation, the net result of the direct and reflex action of the different hues upon the violet sensation is nearly always in favor of fatigue. Fatigue curves show, that the green sensation is also fatigued by most hues, but the fatigue, except by a few colors, is not marked. Reflex curves, on the other hand, show, except for equilibrium colors, fairly distinct enhancements. The red sensation, however, is very difficult to fatigue and shows fatigue only in the extreme red and only when the fatiguing color has a wave length of .480μ or less. According to the sensation curves of König and Dieterici the red sensation curve terminates at about .480μ. It has already been pointed out that the experimental evidence given in this paper, would indicate that the red sensation curve really extends

to the violet end of the spectrum as Exner's curves show.[15] However, the curves of König and Dieterici may be taken as showing, that the direct stimulation of the red sensation by wave lengths longer than .480μ is at least very small. If the fatiguing color is any hue of red or green, except equilibrium colors, the fatigue curves show that the effect of prolonged stimulation is an enhancement of the red sensation, due to the reflex action overbalancing the direct. The reflex curves also show that the red sensation is far more susceptible to reflex stimulation than the other sensations. It must be remembered, of course, that the experimental results were obtained by removing the eye, after strong stimulation for three minutes, to a less intense spectrum upon which the measurements were made. Therefore, when a bright white light is fixated by the author's eye for about 30 seconds it assumes a pink tinge due to the strong enhancement of the red sensation by reflex action. With longer fixation the direct effect overtakes the reflex and fatigue predominates, with the result that the pink tinge disappears leaving a white of a much reduced intensity. Similarly, when a brilliant green color is fixated, the reflex enhancement of the red sensation, which is the sensation predominantly stimulated by the reflex action of green, outgrows the green sensation, which is being fatigued by direct stimulation, thus resulting in giving the color a purplish tinge. Longer fixation again results in favor of the direct action on the green and the color appears a green of a much reduced luminosity and saturation. However, when fixating upon a brilliant red color, the author's red sensation is so difficult to fatigue, and so sensitive to enhancement by reflex action, that the reflex green never outgrows the red, and therefore, no green tinge was ever observed when fatiguing with red.

Although anomalous trichromatism may, in part, be explained as due to a shift of one of the sensation curves, yet the experimental evidence given in this paper shows that a more comprehensive explanation is possible. Since direct stimulation of the retina is always accompanied by a sensory reflex, then any abnormal development of the reflex stimulation must produce at least anomalous results in color vision. In general, therefore, anomalous trichromatism is due to an abnormal ratio of the direct stimulation of the sensations to their reflex enhancement. Since this ratio depends to some extent upon the intensity and duration of a stimulus, it is quite conceivable, as Edridge-Green has observed, that[16] "There are also persons who will make

[15] Parsons: Colour Vision, p. 223.

[16] "Physiology of Vision," p. 223.

normal equations in one set of circumstances and anomalous equations in another." He has also observed, as already referred to in a previous quotation, that some individuals will agree with the normal equation when a red of wave length .670μ is used but will make an anomalous equation with a red of .690μ. Now, .670μ is very close to an equilibrium color which the author found to be at .665μ, while .690μ is a color which gives large reflexes. It is quite possible, therefore, that these anomalous trichromats, examined by Edridge-Green, had an equilibrium color close to .670μ, the stimulation of which would result in a balance being set up between the direct and reflex effects of the color, while the effect of employing a red of .690μ would be to produce abnormal reflex enhancements and consequently an anomalous equation.

The following observations, made by various experimenters, clearly show when viewed in the light of this paper, that the reflex sensation may, under certain conditions and with certain individuals, actually predominate over the direct effect of a light stimulus.

"If the primary stimulus (white) is more intense or acts for a longer time coloration may commence before obscuring the eye (Fechner)."[17]

"A vivid blue-green after image may be seen not only in the absence of all green light but whilst the eye is still being stimulated with a red light."[18]

"The case of a strongly colored red surface whose image extends over the greater part of the retina is especially striking. The colour fades very slowly but steadily, giving rise to a peculiar sensation of loss of power of the eye until the field becomes quite grey and colourless. At this stage the state is one of kinetic equilibrium, and a subjective fluctuation, like those which are always taking place in self light, may suddenly result in a rise of the threshold values of the weak green and blue sensations. If that occurs the colour of the field will suddenly flash into perception as a strong green. The effect is unusually striking, but is not easy to attain."[19]

This last quotation is really a careful description of what may be called the growth of the reflex sensation until the effect of direct action, which affects predominantly the red sensation, is equalled by the reflex action, which enhances chiefly the complementary green, thus

[17] Parsons: "Colour Vision," p. 110.
[18] Edridge-Green: "Physiology of Vision," p. 145.
[19] Peddie: "Colour Vision," p. 175.

resulting in a grey. An equilibrium between the two effects then exists until the reflex enhancement of green suddenly predominates over the direct excitation of red.

THE APPLICATION OF THE PRINCIPLE OF REFLEX VISUAL SENSATIONS TO THE YOUNG-HELMHOLTZ AND HERING THEORIES

The Young-Helmholtz trichromatic theory of color vision with the various modifications and extensions, made by von Kries, Abney and others, furnishes a simple and satisfactory explanation of a great mass of phenomena associated with the perception of light and color. The theory originated out of a study of color mixtures, which are explained by it in a very satisfactory manner. Dichromatic vision is explained as due to the absence of one of the sensations, and monochromatic vision as the identity of all three. Anomalous trichromatism, according to this theory, is due to a partial reduction in one or more of the sensations, or in some types, to a shift in one of the sensation curves.

The theory, apart from the principle of reflex sensations, offers no adequate explanation of the phenomena of after images, for both positive and negative after images may be experienced in the absence of stimulation by white light. If dichromatic vision is due to the absence of one component sensation, it is difficult to understand why a certain portion of the spectrum should be seen as grey and not colored, if the remaining two sensations are stimulated, nor almost completely dark, if none of the sensations be affected. Again, it does not appear consistent to suppose, that dichromatic vision is due to the absence of one color sensation, while monochromatic vision is the identity of the three. The theory is also deficient in offering an explanation for the various types of color blindness with normal luminosity curves. The facts of spatial induction or simultaneous contrast were regarded by Helmholtz as "illusions of judgment," an explanation which abandoned physiology completely.

These researches are not intended to confirm the Young-Helmholtz theory, although they do indicate three fundamental sensations corresponding to red, green and violet. The evidence rather corrects and extends the theory by recognizing the reflex action of light upon the visual mechanism in addition to its direct effect.

This addition of the principle of reflex visual sensations, as discovered by Allen and as extended both by him and in this paper, offers, on the basis of the trichromatic theory, simple and satisfactory explanations for successive and simultaneous contrast, the whiteness underlying

all colors, the saturation of color in after images, complementary colors, anomalous trichromatism, etc. von Kries' duplicity theory, which offers an explanation of scotopic or twilight vision, may yet prove an unnecessary addition, for, as all colors tend to become white at high intensities, due to the reflex enhancement being equal to the direct, so too, the absence of color in all lights at low intensities may be due to another equality between the direct and reflex action of light in stimulating the sensations. It is quite possible that color blindness, either partial or complete, may also be caused by certain balances set up between the direct action of light and the complementary reflex, resulting in grey. The correctness of the above predictions can only be determined, in the first case, by an experimental study of reflexes at low intensities, and in the second by investigating them in the color blind.

The value of any theory is twofold, first, in offering satisfactory explanations of many related phenomena, and second, in stimulating fruitful research. In this respect the trichromatic theory of Young-Helmholtz has become more and more firmly established, until now, in the light of the recent researches in reflex visual sensations, little room seems left for many of the opposing theories. However, it seems quite improbable that a rival theory, which also explains many phenomena of color vision, and which too has stimulated much valuable research, should not contain a considerable degree of truth. Such a theory is that proposed by Hering.

The Hering theory assumes six psychophysical processes, corresponding to the six primary sensations, which may be arranged in pairs, red-green, yellow-blue, white-black. Three photochemical substances are supposed to exist in the retina, one corresponding to each of the three pairs of sensations. The first named sensation in each pair is supposed to arise from the dissimilation of the photochemical substance and the second sensation from its assimilation. All rays of the visible spectrum have a dissimilating action on the white black substance but different wave lengths in different degrees. When mixed light produces equal dissimilation and assimilation in the red-green or the yellow-blue substances, colorless light is the result. The action is not complementary but rather antagonistic, for yellow and blue do not produce white light by their combination, but by destroying each other's effects, and leaving visible the white, which is already there through the dissimilation of the white-black substance by the mixed light. Each visual response is therefore a mixture of the three sensations excited by

dissimilation together with the three arising from assimilation, the resulting color being due to the one of the six that produces relatively the greatest effect.

The principles deduced from the experimental evidence given in this paper show that two opposite effects are produced whenever light of any hue stimulates the retina. The direct and reflex action of light, although apparently antagonistic, produce their full effects without in any way destroying or inhibiting each other. The net result is not the excess of one action over the other, but rather the combined effect of the two. Because of the underlying whiteness of all spectrum colors, Hering assumes the existence of a white-black substance, in which the antagonistic action results in a series of greys. The discovery, however, of reflex visual sensations no longer necessitates this assumption, since white is the result of equal stimulation of the three fundamental sensations, red, green and violet, whether it be by direct action, reflex action, or by a combination of both which it appears must generally be the case.

Both the Young-Helmholtz and Hering theories recognize that the nature of color vision is essentially trichromatic, the former by supposing the existence of three fundamental sensations, and the latter by the assumption of three pairs of psycho-physical processes. The first theory explains most satisfactorily phenomena, such as those of color mixtures, which arise chiefly from the direct action of light; the second, phenomena relating to color contrast, which have now been shown by Allen to be due largely to the reflex effect of a color stimulus.[20] Each theory therefore is mainly based on only one of the two phases of color perception. In the light of a visual reflex of a sensory nature, the Young-Helmholtz and Hering theories can no longer be regarded as antagonistic. The existence of a reflex, affecting predominantly the complementary sensations, explains fully the apparent antagonism of color sensations, which Hering recognizes as an essential feature of color perception.

This investigation is one of a series relating to the reflex influence of light on the phenomena of color vision, initiated by Prof. Frank Allen, to whom I desire to express my thanks for suggestions and for laboratory facilities placed at my disposal.

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[20] J. O. S. A. & R. S. I. 7, p. 913; 1923.

Dependence of the Current-Density in the Glow-Discharge, in the Condition of normal Cathode-Fall, on the Temperature and Shape of the Cathode.—The experiments described in this article are performed with a very large discharge tube, having a cylindrical cathode in the center, enveloped by an anode in the form of a cylindrical gauze; thereby the pressure changes consequent on temperature changes are minimized, the influence of the walls in producing positive column is avoided, and the current density over the cathode surface is rendered uniform. Using as cathode a hollow Pt cylinder with a thermometer inside, Günther-Schulze found that its temperature rose through hundreds of degrees after the discharge was started, the current density meanwhile falling rapidly. At a pressure of 2.75 mm (of air) the final temperature was 618° K, at 5.26 mm it was 775° K. At 5 mm pressure of air the current density to the heated cathode was 6.3 times as great as when the cathode was kept cool by internal water flow; and similar though less pronounced effects were observed in hydrogen, and when the hollow electrode was replaced by a massive cylinder of copper 16 mm thick. It therefore makes a great difference what the cathode temperature is (it is probably the temperature and density of the gas in the Crookes dark space which actually makes the difference) at the moment of measuring the current density, and previous work is vitiated by neglect to consider this. With the water cooled cathode the current density was found proportional to the square of the pressure of the gas. This affects wires and thin cylindrical cathodes the most; water cooling cannot be applied, nor can the measurement be made quickly enough to anticipate the temperature rise; and measurements with cathodes of various radii of curvature must be made after the cathode has reached temperature equilibrium, and be intercompared with the realization that they relate to different temperatures. Actually it is found that the current density rises very rapidly as the curvature of the electrode is increased. Measurements on the water cooled cathode above described showed that the current density increases as the square of the pressure in hydrogen and as the 1.8 power in air. Many observations were made with cathodes bent into cup or wedge shapes; inside the wedge or cup, or, more generally, wherever two cathode surfaces are opposite and close together, the current density rises sharply and the Crookes dark space becomes narrower. This is ascribed to electrons from one surface getting over into the Crookes dark space above the other surface and generally distorting the fields by their space-charge effects. A cathode consisting of a platinum surface, with an aluminium ribbon so wound over it that the surface is 2/3 Pt and 1/3 Al, is completely covered (Pt and Al alike) with a glow having a cathode fall intermediate (276 volts) between that of Al (258) and that of Pt (344).—[A. Günther-Schulze, (Reichsanstalt) ZS. f. Phys. *19*, pp. 313-332; 1923].

K. K. DARROW

INSTRUMENT SECTION

A SUPERIOR ELECTRIC PENDULUM; AND SOME PENDULUM EQUATIONS

By Walter P. White

The type of pendulum here described is not new, but was known at least as early as 1854.[1] With respect to the highest precision it is probably equal, tho not markedly superior, to the other best types now known; in ease of construction it seems to excel all others, crude or refined; it almost certainly excels in combining the two merits. The object here is chiefly to call attention to the almost ridiculous ease with which, by its use, a time-keeper of very high precision can be obtained; the simple equations given for determining how this can best be done are also applied to the problem of securing the highest precision, with this and other types of pendulum drive.

The mechanism here presented is essentially an electrically operated gravity pendulum drive. The driving force, being a weight, is absolutely constant, while the electric operation avoids almost as absolutely all friction capable of influencing the rate. The essentials are shown in Fig. 1. The arm w is lifted at each stroke by the arm l from the stop s at h, and is dropped back on the stop s at the lower point k. The fall of the weight from h to k furnishes the rigorously constant power for keeping the pendulum in motion. This power is supplied by the magnet n which moves the stop between h and k in response to the electric contact at c between the arm l and the arm w. The current thru n serves also to operate the "slave" pendulum or other device used for counting the swings of the master pendulum, and it also affords, as a by-product, time signals far more precise than are given by the Riefler or some other accurate time-keepers.

It is possible to vary the length of the arm w, its weight, and the times at which that is lifted and dropped. These quantities should be so chosen as to reduce to a minimum the effect of irregularities. The effects of slight friction at the contact c, or rather, of variations in such

[1] Liais and Tiede seem to be the originators; see W. Foerster, Astron. Nach., No. 1636, p. 55, 1867; for modern accounts: T. Hayn, ibid, No. 4594, 1912; Ch. Féry, J. de Physique 7, p. 520, 1908; Ralph A. Sampson, Proc. Roy. Soc. Edin., *38*, p. 169, 1918; the same in Glazebrook's Dictionary of Applied Physics, *3*, p. 213. (The reference here to Foerster seems to be incorrect.) Useful summaries of information on pendulums are also: Article on clocks in Encycl. Brit., 11th ed.; H. R. A. Mallock, Clocks and their errors. Proc. Roy. Soc., *85*, p. 505; 1911.

friction, of tremors, and of sticking of the contact, also demand consideration. Two experimenters have reported a change in pendulum rate resulting from a change in the strength of the current thru the magnet. The possible effective causes of this error seem to be: Bending of an insufficiently rigid system; shocks as the armature comes against its stops; direct magnetic action upon some part of the pendulum itself; failure of the armature to get moved and come thoroughly to

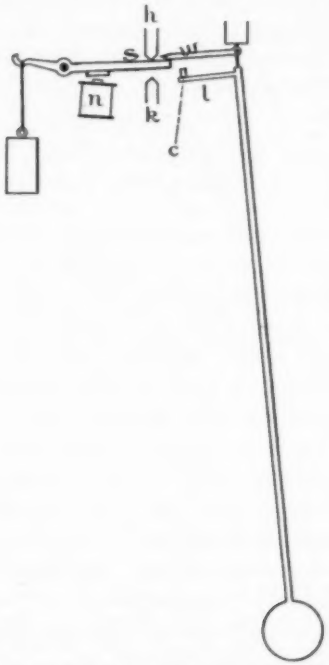

FIG. 1. *Essentials of the electric gravity pendulum drive.*

rest quickly enough. All these last sources of error can be avoided, and until it is known which of them are really effective it seems to be best to make all safely negligible.

EQUATIONS FOR THE RATE

The effect which this method of driving has on the rate is easily found by using the circle of reference. In Fig. 2 let the diameter AB represent the angular motion of the pendulum, q any instantaneous (angular) position of it. The radius OB then represents the half angle

of swing, a. Then, since the motion is harmonic, the point P travels with uniform velocity around the circle, thus representing time, and the ordinate y is proportional to the velocity of the bob.

When the weight is put on the arm l, the change in velocity is negligible.[2] Hence the effect of putting the weight on is adequately taken account of by considering that the position of equilibrium of the bob is thereby shifted. Thus if the weight is lifted by motion to the right when $Oq = x$, the center of the pendulum arc is instantly shifted to the left, say to O'. But the velocity y is not appreciably changed. Hence the oscillation is completed by a motion which in the circle of reference appears as a rotation about O' onward from the point P, along, say, PB'. If the figure $O'PB'$ is now moved to the right (Fig. 2b)

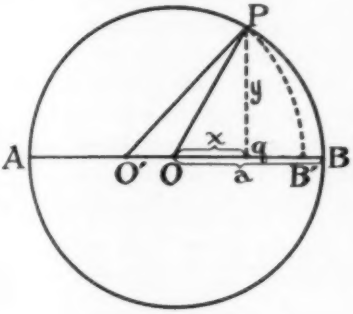

FIG. 2a

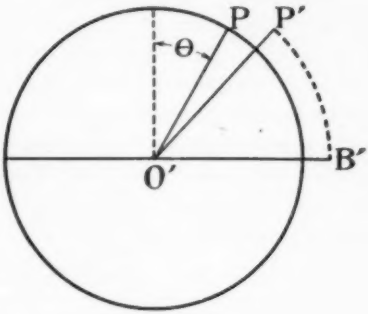

FIG. 2b

so that O' falls on O, it is clear that the time of oscillation has been shortened by omission of the arc POP'. A similar shortening occurs if the pendulum drops the weight.

Considering that the angle POP' is actually very small indeed we may put $POP' = \frac{PP'}{a} \cos\theta$, where θ is the angle in the reference circle between OP and the vertical, whose sine is x/a. For the small angles of swing actually in question, PP', equaling the shift of equilibrium position OO', equals $\frac{ml}{ML}$ when m and M are the masses of weight and pendulum bob, respectively, and L is the length of the pendulum. With $M = 8000$ g, $m = 0.5$ g, $\frac{1}{L} = 1/5$, $a = 0.03$, which are the values

[2] This is shown below.

with our seconds pendulum, $\frac{PP'}{a}=\frac{1}{2400}$. The maximum value for the gain in rate, equal to $\frac{POP'}{\pi}$ is therefore of the order of 10 seconds a day. For high precision this must be kept constant at least to 1 per mille. Any other pendulum driving apparatus would encounter necessarily a similar requirement, and usually in a less simple and manageable form. If we put s for the angular shift OO', the gain in time, ΔT, for one half cycle of a seconds pendulum is:

$$\frac{\delta T}{T}=\frac{s\cos\theta}{\pi a}=\frac{s\sqrt{a^2-x^2}}{\pi a^2} \tag{1}$$

Here a, s, and x, which appear in the reference circle as straight lines, are, physically, angles; of swing, of shift, and of contact with the driving weight respectively, while θ, which appears as an angle, is actually the time elapsing after the middle of the swing before contact occurs.

Of the 3 instrumental constants occurring in this equation, s will change during the running of the pendulum only if the axis of rotation of the arm w changes its position, and the magnitude of the resulting error is easily seen. The effect of changes in x, the effective position of the stop, and in a, the amplitude of swing, can be investigated by differentiating (1). We get:

$$\frac{dt}{T}=-\frac{s}{\pi a}\tan\theta\frac{dx}{a} \tag{2}$$

$$\frac{dt}{T}=-\frac{s}{\pi a}\frac{\cos 2\theta}{\cos\theta}\frac{da}{a} \tag{3}$$

In applying these equations to discuss possible errors, it is necessary to consider that for maintaining the motion it is not ml, the moment of the weight, proportional to s, but the work done by the weight, which must have a given value set by the logarithmic decrement, that is, by the rate at which the pendulum loses energy by swinging.

This work per cycle is $mgl\,a(\sin\theta_1-\sin\theta_2)$, where g is the acceleration of gravity, and $a(\sin\theta_1-\sin\theta_2)$ is the angle thru which m acts. The subscripts 1 and 2 refer to the lifting and dropping of the weight respectively. For a given pendulum and amplitude the work is constant, hence ml, and therefore the shift s are inversely proportional to $\sin\theta_1-\sin\theta_2$. We should, then, substitute for s, $k/(\sin\theta_1-\sin\theta_2)$ in discussing[3] the effect of permanent changes in θ, k being a constant for

[3] The energy of the pendulum is $\frac{MgLa^2}{2}$; that required per cycle is $2fMgLa^2$ if f is the logarithmic decrement, or $2f$ the proportional loss of energy per vibration; this should equal

such changes, and actually equal to $2f\,a_0$, or twice the average loss of amplitude per half cycle. Equation (2) thus becomes[4] for either half cycle:

$$\frac{dt}{T} = -\frac{2fa_0}{\pi}\,\frac{\tan\theta}{a(\sin\theta_1+\sin\theta_2)}\,\frac{dx}{a} \tag{4}$$

The causes of a variation, or error, in x are wear of the contact surfaces, c and s (Fig. 1), and warping of the whole apparatus or its supports. Both these causes will affect x_1 and x_2 alike if the stops, h and k, are made in the same block of metal, as they easily can be. If x_1 and x_2 are symmetrical with respect to the center of the swing ($x_1 = -x_2$), any small common shift will cause equal errors of opposite sign, which will cancel completely as long as the symmetry is not destroyed. The resultant error will thus be very small, and will depend on the rate at which the two contacts cease to be symmetrical. To find it we may differentiate $\tan\theta$ in (2) with respect to x, obtaining $\frac{1}{\cos^3\theta}\,\frac{dx}{a}$, which shows that the mean value of $\tan\theta$ over a shift dx is $\tan\theta \pm \frac{1}{2}\,\frac{1}{\cos^3\theta}\,\frac{dx}{a}$, and then substitute this latter value for each half of the cycle in (4), obtaining for the effect of a shift of symmetrical contacts:[5]

$$\frac{2fa_0}{2\pi a}\,\frac{1}{2\sin\theta\cos^3\theta}\left(\frac{dx}{a}\right)^2 \tag{5}$$

This is a minimum for $x = \frac{a}{2}$.

Equation (3) shows that the error from change of amplitude is zero for $\theta = 45°$ ($x = .707a$), and that for values of θ greater than that the

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$mgla(\sin\theta_1 - \sin\theta_2)$. From these equations it follows that if a, the amplitude, is increased ml must increase accordingly; the resultant increase in the shift, s, is proportional to the increase in amplitude; hence the increase in rate due to the driving mechanism is not greatly dependent on the amplitude.

[4] From this it appears that the error from a shift in the position of a stop is largely independent of the value of x as long as x is not a rather large fraction of a.

[5] Numerical examples are easily worked by the aid of a 4-place table of squares and square roots, starting with the original change of time of (1) expressed in terms of x and a. For the symmetrical case (1) thus becomes

$$\frac{fa_0}{\pi a}\left\{\frac{\sqrt{a^2-(x+dx)^2}+\sqrt{a^2-(x-dx)^2}}{(x_1-x_2)}\right\} \tag{6}$$

It was thus found that for $dx = 0.05\,a$ the error with symmetrical contacts was 0.004 times f/π for $x = 0.5a$ and only 0.0075 $\frac{f}{\pi}$ for $x = 0.8a$. These correspond to 0.055, 0.1, seconds a day, taking f as 0.0005. For $x = 0.05a$ the error according to (6) is $0.025\,f/\pi$ or 0.34 seconds a day, but (1) is not exact for the large values of s involved in this case.

error can be made opposite in sign to the "circular" error of the pendulum itself, thus affording a possibility of eliminating the circular error altogether. The exact arrangement for doing this can be worked out for the particular case by means of a table of natural sines and cosines, treating the change of amplitude, which may reach 3% to 6% in air, as a finite quantity. If one contact is at the middle of the swing, its amplitude effect can be compensated by putting the other at $\theta = 60°$ ($x = 0.866$). With spring-suspended pendulums the circular error may be very small, and its determination involves an amount of difficulty which is not likely to be incurred unless the very highest precision is desired. But as far as this particular error is of importance, symmetrical contacts should be at least as far out as $\theta = 45°$ ($x = .707$), or a central contact should be combined with one out at least as far as $\theta = 60°$.

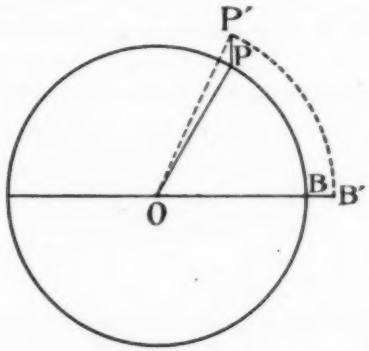

FIG. 3

In order to compare the effectiveness of this pendulum drive with that of others, a glance at their functioning is in order.

1. *Impulse driving.* A highly esteemed form of drive is one that may be called the trigger class of escapements.[6] By means of an unlocking device, which is an unavoidable but not serious drawback, the pendulum is given a very short push, or impulse, at the very center of its swing, and is quite free at all other times. The law for this kind of drive may be seen from the circle of reference, Fig. 3. The effect of the impulse is so to increase the velocity that the amplitude is represented by the outer, dotted, arc $P'B'$. The increase in amplitude, PP', is fa, multiplied by a function of cosine θ, which is about unity

[6] Enc.-Brit. Article, p. 543; Dictionary of Applied Physics, p. 214.

near the center of the swing, and hence may be neglected in comparison with sine functions. The change of time is evidently

$$T\frac{POP'}{\pi a}, \text{ or } T\frac{fa\sin\theta}{\pi a}, \text{ or } T\frac{f}{\pi}\frac{x}{a}, \tag{7}$$

and the proportional effect of an error in x is

$$\frac{\delta T}{T}=\frac{f}{\pi}\frac{dx}{a} \tag{8}$$

A comparison of (5) and (8) shows that the trigger escapement involves a much larger time error from an error in x, especially when this error (dx) is small, than the symmetrical arrangement of the electric gravity drive. The main advantage of the trigger escapement is that miscellaneous shocks arriving thru the driving mechanism, which are impulses, can only act on the pendulum when sin θ is zero, and then their effect on the rate is nil. In mechanically driven clocks the trigger escapement also eliminates most of the error from irregularity of the driving force, but this evidently constitutes no point of superiority over a gravity drive.

2. *The Riefler clock.* The Riefler clock is to be classed with the gravity-driven, since an opposing force meets the pendulum and follows it on the return beyond the point of first contact. The force is applied, not by a weight, but by a spring fastened to the pendulum, whose further end is moved by the escapement wheel. That this spring is also the supporting spring of the pendulum is an interesting and important detail of the escapement mechanism, but does not appear to have any particular effect on the rate. Some essential features of the action of the Riefler mechanism are hard to understand from most accounts—particularly misleading is the Encyclopaedia Britannica, which actually classes it with the Graham escapement!—but Sampson[7] supplies the most necessary details. Each half cycle may be divided into 5 stages. (1) During the first half of the stroke each way the end of the spring is locked against the escapement wheel, and the spring is unbending, accelerating the pendulum. (2) At the center of the swing the spring becomes straight and unlocked, and begins to pull a pallet off the escapement wheel. The pendulum furnishes some of the power for this motion, which occupies 0.1 of the swing (0.2 of a). The spring remains nearly straight, and the pendulum is practically turning on the knife edge which supports the farther end of the spring. (3) Free from the escapement wheel the pendulum, with the spring straight, continues

[7] Proc. Roy. Soc. Edin., op. cit.

its oscillation about the knife edge which supports the spring. Meanwhile the released escapement wheel is turning to meet it. (4) After an arc of about $0.1a$ has been traversed by the free pendulum a tooth of the wheel strikes a pallet on the anchor attached to the spring, and begins to bend the spring back, bringing its upper end to the central position after the pendulum has traversed an arc of about $0.2\ a$ more. This bending opposes the motion of the pendulum, and corresponds to the lifting of the weight in the gravity-escapement. It is accomplished at a mean angular distance from the center of the swing of about $0.4a$. (5) The wheel and the bent spring are now locked together, and stay so till the pendulum has unbent the spring at the middle of the return swing. Meanwhile the pendulum first completes the swing, traversing an arc of $0.5a$, bending the spring just as if this were permanently vertical at the top, like the supporting springs of other pendulums.

Advantages attributed to the Riefler mechanism are the diminution of shock secured by transmitting all force thru the spring, the central location of the releasing of the escape wheel, and the freedom of the pendulum at the ends of the swing. It is evident that the last two are very imperfectly secured. One apparent source of error, which seems to have no counterpart in other pendulums which are in the same class as to precision, is the variation in the point at which the counter pressure is applied to the spring. This counter pressure begins when the escapement wheel, after being released and traversing a certain arc, meets the pallet on the pendulum. The point of beginning contact therefore depends on the speed with which the wheel turns, and this will vary with the condition of the lubricating oil. Now the pressure of the spring is analogous to the picking up of the weight in the gravity pendulum, and an increase in the abscissa of the average point at which it occurs affects the rate like an increase in the x of equation (2), tho according to a different law. Adding the tension of a spring which is relaxed at the central position evidently does not change the center of the stroke, but it does accelerate the rate, and the later the spring is applied the less is the time during which the pendulum is moving at the faster rate. Mr. Paul Sollenberger of the U. S. Naval Observatory, however, informs me that their 3 Riefler clocks, which have been carefully watched for years, show an *increase* of rate (totaling about 0.2 seconds a day) in the first few months after oiling. The explanation of this is apparently to be sought in the effect of the pulling loose of the pallet from the escapement wheel, which is a negative impulse at an

average position of 0.1 a from the center, and whose increase through increased friction will therefore cause an acceleration of the rate. (See Fig. 3). It is only friction at the pallets that does this; friction in the train, by reducing the pressure and so the friction, on the pallets, diminishes the rate. The success of the Riefler mechanism, therefore, depends on a fortunate or skilful compensation of two effects, each of which alone looks like a defect; that of friction at the pallets, which accelerates, and that of friction in the train, which retards. The Riefler mechanism is generally described as delicate, requiring very accurate construction and adjustment.

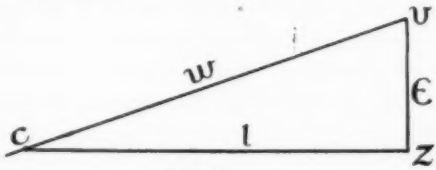

FIG. 4a

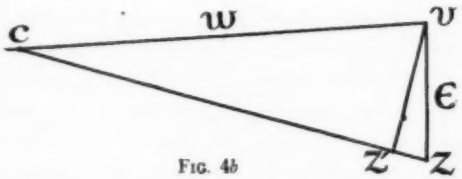

FIG. 4b

Féry has attributed great importance to friction at the contact, c, of Fig. 1, and without endorsing his opinion we may consider it worth while to inquire into the possible amount of this friction. The cause of it will evidently be a failure to secure coincidence in the axes of the levers w and l. In fig. (4a) let ϵ be a vertical distance between the axes of the arms w and l and let l be horizontal. Then the distance zc along l will be determined by w and ϵ and by the angle at z, which has been taken as initially a right angle. Rotate w and l, say, upward keeping w constant in length (fig. 4b). Draw vz' perpendicular to l. If the angle thru which w has been rotated is small the difference between vz and vz' will evidently be small compared to zz', and may be neglected, while the difference between zc in 4, a and $z'c$ in 4, b is smaller still. Hence the distance zc is changed by the amount zz' when l is rotated. This change of distance is clearly the distance thru which rubbing takes place at c, and is equal to ϵ times the small angle of rotation. It is independent of the length of l. Any rotation not terminating

in a horizontal position can be treated as the algebraic sum of two, each of which does so terminate. A displacement along *l* of one of the axes evidently has, for small rotations, an effect negligible compared to that just considered. It follows that since the relative motion due to lack of coincidence of parallel axes is independent of the length of the arms, while the weight is inversely proportional to that length, the friction will increase as the arms become shorter. The relative motion due to lack of parallelism of the axes, however, will be proportional to the length, hence friction from that cause will be independent of the length.

Shocks. The most serious source of shock, as far as the electric gravity drive itself is concerned, appears to be the striking of the lever, *l*, against the stops *h* and *k*. It seems difficult to avoid communicating some of this shock to the pendulum supports, since the stops should remain in unvarying relation to the axis of rotation of the pendulum. The interposition of cushions might favor some shifting of position, and an independent support might lead to some relative displacement thru differential expansion. It seems best, therefore, to rely on the following mechanical devices: (1) Making the common support of the pendulum and of the steps rather massive; and diminishing the shock by (2) Having the arm, *l*, absolutely as light as is consistent with the necessary rigidity; (3) Having the arm as short as is convenient; (4) Avoiding all unnecessary force; (5) Suitably balancing the opposing forces; (6) Damping the motion, as with an oil or air dash pot. The last two devices, which are employed in our apparatus, apparently constitute an improvement in this type of pendulum drive. To balance the forces the spring ordinarily used to return the armature is discarded, as sufficiently variable in its properties to cause danger of failure thru getting out of adjustment. Weight control is used, and the armature in its travel picks up an extra weight, and might well do so twice. Thus when the armature is near the pole faces, where the magnetic pull is strong, a relatively strong opposing force tends to diminish the velocity and the shock of contact, and to start the armature back promptly when the magnet current is stopped; while a weak counter-pull at the far end of the stroke adds little further velocity to the armature and allows a weaker pull of the magnet to start it forward.

The shock when a pendulum rod, about 10 cm from its axis, comes in contact with a weight of 1 gram, would seem to be negligible. The energy taken by the weight is of the order of one-millionth of that pos-

sessed by an 8-kg pendulum, and it is only the slight variations in the shock which cause error. The effect on the rate can also be reduced to zero by having the pick-up occur at the center of the swing, tho this deprives the pendulum of the advantage which comes from the symmetrical arrangement of the stops.

In spite of its small magnitude, the shock at pick-up seems to deserve mathematical statement. When the pick-up occurs, the moments of inertia of pendulum and weight[8] are, respectively, ML^2 and ml^2. Since the angular momentum remains constant the change in angular velocity $\delta\omega$, is $\frac{ml^2}{ML^2}\omega$. In the reference circle (see Fig. 3) ω is $\pi a \cos\theta$. (This equation has to do merely with the geometry of the reference circle, and need not be scrutinized as to its dimensions.) Hence the line PP' (whose sign is now opposite to that in Fig. 3, since the impulse is now a retardation, not an acceleration) which represents the loss of velocity, is $\frac{ml^2}{ML^2}\pi a \cos\theta$, its projection on the circumference is the same multiplied by $\sin\theta$, and the loss of time per *cycle* is

$$\frac{\delta T}{T} = \frac{ml^2}{ML^2}\,\frac{\pi a \cos\theta \sin\theta}{2\pi a} = \frac{ml^2}{2ML^2}\cos\theta\sin\theta \qquad (9)$$

But $\frac{ml}{ML}$ has been shown to be $\frac{2fa_0}{\sin\theta_1 - \sin\theta_2}$.

Putting this expression in (9) we get:

$$\frac{\delta T}{T} = \frac{fa_0}{\sin\theta_1 - \sin\theta_2}\,\frac{l}{L}\cos\theta\sin\theta \qquad (10)$$

This shows that for the symmetrical case the change of rate from the impulse of the pick-up, and therefore the most probable error from it, decreases with the amplitude, a, with the length of arm, l, and with cosine θ, or the velocity at pick-up.

Sticking of the contact. There is a possible impulse from sticking of the electric contact, c, (Fig. 1) as that is broken. The energy of this is evidently equal to the force required to break, multiplied by half the distance the pendulum bob must travel while accumulating deformation sufficient to develop this force. A measurement of these two quantities in our pendulum, where the chief deformation was the bending of an unusually flexible pendulum rod, showed that the energy

[8] If the "weight" is a bar of uniform section its moment of inertia is only 2/3 that of a weight giving the same pressure on the stop, but the difference of 1/3 is of little practical importance.

required was one six-billionth of that possessed by the pendulum, unless the current was much over 0.1 ampere. More detailed discussion of this error therefore seems superfluous.

Friction at the contact, c. Altho friction at c is necessarily very small indeed, on account of the small motion and light pressure, it undoubtedly should be excluded, since it offers a series of irregular impulses which are not confined to the central part of the swing. We have seen that it is proportional to the lack of coincidence in the axes of the levers w and l. Effective coincidence can doubtless be increased by having a separate lever for l, whose bearing, whether spring, knife edge, or pivot, can be made a duplicate of that of w, and carefully aligned with that; l is then joined to an arm on the pendulum itself by a short straight spring. A practically absolute elimination of friction can also doubtless be secured in nearly all cases, as in our pendulum, by a device due to Féry.[9] A very fine straight spring steel wire 3 cm long (say) is fastened at right angles to one of the arms, and carries at its end a little gold ball, which bears against a gold plate on the other. Such a wire can apparently be trusted not to buckle under a pressure of 1 gram, and yet to give sideways at the end from 5 to 20 hundredths of a millimeter easily enough to avoid friction, which is all it has to do.

The electric contact. An obvious possible difficulty with the electric gravity drive is that of maintaining for long periods of time satisfactory electric contact under the light pressure of 1 gram or half that, with friction carefully excluded. Indeed, anything like that has been declared to be impossible. Our pendulum, however, has usually run for nearly a year, then to be stopped by the formation of a small amount of fine black powder on the contact surfaces. Hayn,[10] who ran continuously for many years an electric gravity pendulum that was probably better inclosed than ours, reports finally having such a powder, which he was quite sure was of carbonaceous material, presumably formed from dust or hydrocarbon vapor. We failed to detect gold in our black powder, but the amount was so very small that the negative result is not conclusive. Probably, however, Hayn is correct, and in that case a thoroughly inclosed electric gravity pendulum could be expected to run without any attention whatever for more years than a Riefler clock remains at maximum constancy, and the making of a fresh start would call for practically no more time and labor than is required to get at the pendulum. For a pendulum not too well inclosed to be accessible the contact surfaces can easily be wiped in 2 or 3 seconds,

[9] Op. cit. [10] Op. cit.

without interrupting the running, and usually without even turning off the current. This trifling attention, given once in, say, 6 months, should secure indefinite continuous operation.

Position of the Magnet. In our pendulum (Fig. 5) the magnet is behind the invar rod, and the armature lever carrying the stop, *s*, comes forward. This seems a very satisfactory crude arrangement, but it may not get the magnet as far away as is desirable, and it certainly causes a decided lack of parallelism in the motions of the armature lever and the lever, *w*, at *s*. This tends to cause more wear at *s*, resulting in a very slow change of rate. As arrangements which are probably better for clocks aiming at the highest precision, and which do not greatly increase the inertia of the moving parts, there may be suggested: (1) Putting the magnet, the armature, and a short armature lever well away from the pendulum, above or at the side, and connecting to the stop lever thru either a long axis or a very slender wooden rod always under tension.

Choice of designs. It follows from the preceding discussion that there is no design which is best under all conditions. The design should be varied in opposite directions according to the errors which are deemed most menacing. Error from displacement of the stops is diminished by large amplitude, long levers, and the symmetrical arrangement. Error from shock is diminished by small amplitude, short levers, and a pick-up at the center. In all cases, however, it is desirable to diminish direct magnetic action and shocks from motion of the armature, and to have one, at least, of the contacts 0.7 of the way out or more, in order to diminish, first, the amplitude error, and second, the driving moment, and with that all the errors possibly arising from the driving arrangement.

It seems quite possible that even with the symmetrical arrangement and moderate values of *a* and *l* the errors from shock might be negligible; almost certainly in work of less than maximum precision. The error from shift of contacts should be capable of fairly close estimation in any case. If the errors seem to be about balanced, or in case of doubt, two reasonable compromises seem to be: (1) To make the stop error very small by using the symmetrical arrangement and thus have a little freedom to diminish shock by using small values of *a* and *l;* (2) To eliminate the shock error by a central pick-up, and so be at liberty to increase *a* and *l* in order to cut down the stop error.

Comparison with other kinds of drive. Since the Riefler seems to be a mechanism similar to the gravity-driven, but with a relatively large error, which is closely compensated by another error from which the

gravity drive is quite free, a comparison between them seems possible only on a basis of performance, for which adequate data are not available. It is hard to see any source of error which should make the gravity drive less accurate than the Riefler, and its greater simplicity and cheapness and less need for attention are in its favor.

Some comparison with the trigger escapement seems possible. When the gravity driven pendulum has once picked up the co-axial driving lever its further motion is as *free* as that of any other pendulum whatever. The gravity and the trigger drives are most alike when the gravity picks up at the center. Shock error is then absent from both, and the law for error from displacement of the impulse is about the same. But the trigger escapement gets its impulse at the end of the pendulum rod, so that a given displacement in millimeters means a less angular displacement, and therefore less error. Against this gain is to be put the fact that the impulse with the trigger escapement is more violent because briefer and is brought about in a less simple way, with more chance of displacement thru wear or otherwise. Moreover, if the slight shock at pick-up should be proved to be small and regular enough to be quite negligible, as is probably often the case, the gravity drive with symmetrical arrangement would altogether excel in precision as it does in simplicity.

In the Dictionary of Applied Physics, *3*, p. 213, occurs this criticism of the Electric Gravity Drive.

"All these constructions are open to two objections. The weight of the impulse piece must be considerable in proportion to the energy it has to convey, since it is only the difference of its excursion upwards and downwards that tells; and as it must not be picked up near the end of the excursion it has to be done when the pendulum is moving with considerable speed, and therefore with an impulsive stroke that results in vibrations."

This criticism seems unjustified in nearly every particular. (1) We have seen that the "difference of the excursions upwards and downwards" not only may but should on every account be a large, perhaps a major, fraction of the total excursion. (2) There is absolutely no reason why the impulse piece "must not be picked up near the end of the excursion." There may be a reason why this preferably should not be done, namely, that a great advantage, the practical elimination of all shock effect, may be gained by a pick-up at the center. But this is anything but an argument against a system where the central pick-up is always possible. (3) There remains the notion that the shock of a central pick-up may "result in vibrations" and therefore may be

appreciably detrimental. In the first place, this notion rests on the idea, which we have seen to be false, that the impulse weight must be

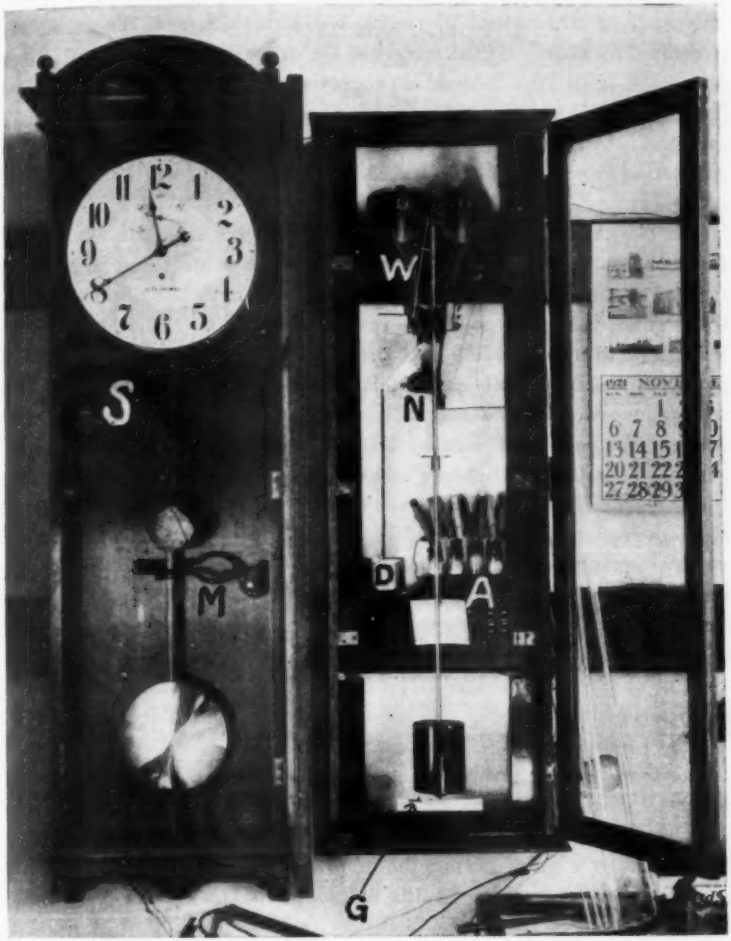

FIG. 5. *Electric gravity pendulum at the Geophysical Laboratory. W, driving weight or arm; here nearly vertical; the lever L of Fig. 1 here coincides with the upper part of the pendulum rod; N, the driving magnet; D, dash-pot damper; A, aluminum cells for spark quenching, now replaced by a condenser; G, sliding gauge for recording the maximum amplitude reached during a given period; S, slave clock; M, its driving magnet.*

relatively heavy, on account of its short effective excursion. The incorrectness of the notion can be further shown in a comparison with

the trigger escapement, recommended by the same critic. The production of "vibrations" by the shock is a question of energy, and therefore proportional to mv^2. If we take v for the velocity of the pendulum bob, the shock of striking a 1 g. driving weight 10 cm from the axis is proportional to $0.01\ v^2$. If the trigger of the other device weighs only 10 mg the shock of striking it alone is proportional to $0.01\ v^2$, or equally great, with the probably much larger shock of the impulse itself still to be counted. Apparently the Dictionary's criticism fell into error by neglecting the effect of velocity, as well as by exaggerating the amount of weight.

The Geophysical Laboratory pendulum.[11] Our pendulum, on the wall in an ordinary laboratory room, is not capable of affording an adequate test of the electric drive. Hence its constancy, usually as good as 0.1 second, has no particular experimental value. The thing chiefly sought in its construction was precision in giving time signals. The precision attained is at least 0.001 second, the limit of the method of testing, which is quite satisfactory. The pendulum is permanently connected to a 56-volt storage battery and runs steadily without any attention whether the battery is charging or not. The current is 20 m.a. One contact is central. The lever w is 20 cm long. Since a sufficiently rigid lever of that length weighing 1 gram did not seem practicable, a vertical spring-suspended lever is used which presses sideways with a fraction of its weight against the pendulum rod itself. This lever, on account of its vertical suspending springs, probably moves in an arc very nearly coinciding with that of the pendulum, which minimises friction at the contact, but by its relatively great mass it magnifies the impulse or shock effect, and we do not recommend its type for the highest precision in time keeping.

Summary. Attention is called to the great ease with which a very accurate clock pendulum of the electric gravity type can be built. Simple equations are given showing how the design may be ordered to diminish the recognized errors inherent in the method of driving. These equations are used to discuss the value of this and other types of drive for pendulums of maximum accuracy, and indicate that the electric gravity drive equals, and possibly excels, the best of other types for such service.

GEOPHYSICAL LABORATORY,
CARNEGIE INSTITUTION OF WASHINGTON,
MARCH, 1924.

[11] Grateful acknowledgments are made to Mr. E. B. Lapham of the Seth Thomas Clock Company who gave us an excellent invar pendulum rod at a time when to procure it otherwise would have been very difficult for us.

A METHOD OF CALIBRATION FOR TROWBRIDGE'S PRESSURE INDICATING APPARATUS

By Crandall Z. Rosecrans

Prof. Augustus Trowbridge of Princeton University has recently published[1] a description of a method of recording vibrations (sound, electrical, mechanical, etc.) by photographic means. One of the applications of the method discussed is the recording of the rapidly varying pressures in the cylinder of the internal combustion engine.

The pressure measuring device described by Prof. Trowbridge is shown in Fig. 1. It consists of an indicator body, which is screwed into the engine cylinder, and which carries a thin steel diaphragm exposed on one side to the cylinder pressure and on the other to the atmosphere.

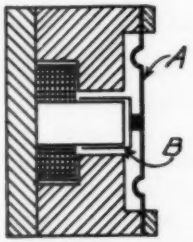

Fig. 1. *Pressure Measuring Device.*

A small coil of fine wire, B, wound on a form attached to the center of the diaphragm, and moving with the diaphragm, is so placed that it moves between the poles of an annular electromagnet. By connecting the terminals of the coil B to a string galvanometer the electromotive force induced in the coil by a motion of the diaphragm may be recorded on a moving photographic film. The galvanometer deflection is necessarily proportional to the velocity of the coil in the field, if the intensity of the field is kept constant. This velocity is in turn proportional to the rate of change of pressure on the diaphragm.

As stated in the original description of the apparatus, the method has many advantages for measurements on internal combustion engines, chief of which are its comparative freedom from inertia effects and the fact that the recording apparatus (galvanometer and film camera) can be set up and operated at any desired distance from the noisy and

[1] Journ. Franklin Inst., *194*, pp. 713-728. Also Power, *53*, pp. 704-708.

vibrating engine. A further advantage is the fact that the instrument gives a record on a uniform time basis, thus lengthening out the critical parts of the cycle at ignition, valve openings, and other important events. For these reasons the indicator should find considerable use in engineering laboratories.

It is evident that the record produced by this instrument is a curve of $\frac{dp}{dt}$ against the time, where p is the cylinder pressure and t the time. This curve may be converted into the more usual pressure-time curve by constructing geometrically the integral curve of the recorded $\frac{dp}{dt}$ curve. The integral curve will show the variation of the pressure with respect to time, but will not in itself furnish a diagram of any known scale. Hence the *magnitude* of the pressure at any instant cannot be determined, either from the $\frac{dp}{dt}$ curve or the p curve.

In order to determine a pressure scale for such a recording instrument, the following method of calibration was devised.

Notation

D = galvanometer deflection as recorded.
x = displacement of the center of the diaphragm.
p = pressure on diaphragm.
t = time.

The galvanometer deflection is proportional to the velocity of the coil B in the electromagnetic field. Hence

$$D = k_1 \frac{dx}{dt} \tag{1}$$

By applying known fluid pressures and measuring the corresponding displacements of the center of the diaphragm it is found that the deflection is directly proportional to the pressure.[2] Or

$$x = k_2 p \quad \text{or} \quad dx = k_2 dp \tag{2}$$

Combining (1) and (2),

$$dp = \frac{dx}{k_2} = \frac{D\,dt}{k_1 k_2} \tag{3}$$

From Fig. 2 it is evident that Ddt represents an element of area under the curve of D against t, which is recorded by the galvanometer. Therefore, integrating, we get an expression for p_1 at any instant t_1.

[2] In order to secure a straight line relation between pressure and displacement it may be necessary to make the diaphragm with a corrugation concentric with the circumference.

$$p_1 = \frac{1}{k_1 k_2} \int D \, dt = \frac{A}{k_1 k_2} + p_0 \tag{4}$$

where A is the area under the curve from the time $t=0$ to the time $t=t_1$ (taking into account the time scale of the diagram), and p_0 is the pressure per unit area on the diaphragm when $t=0$.

It only remains, therefore, to determine the constants k_1 and k_2.

To determine k_1 it is necessary to cause the diaphragm center to execute a motion with a known velocity and to measure the corresponding galvanometer deflections. Then from equation (1) the value of k_1 is easily determined.

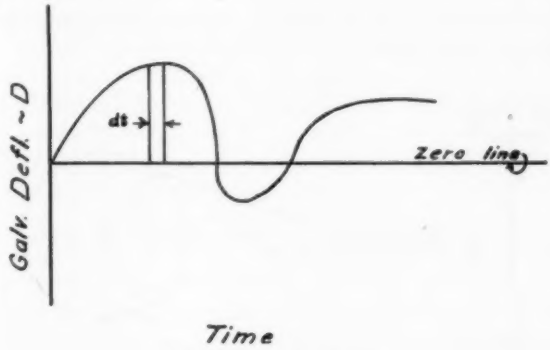

FIG. 2. *Recorded Curve.*

In order to produce a known velocity of the diaphragm center, a crank and crosshead mechanism was made use of (Fig. 3). If the crankshaft is revolved at a constant known rate of speed, the rod B moves with a variable velocity which can be calculated for any given instant.

From the geometry of the crank mechanism (Fig. 3) the displacement of the rod B for any angle θ of the crank is (considering the effect of the angularity of the connecting rod C)

$$x = r \cos\theta + \sqrt{L^2 - r^2 \sin^2\theta} - \sqrt{L^2 - r^2} \tag{5}$$

where L is the length of the connecting rod and r is the crank radius. θ is measured from the dead center position of the crank. Then

$$\frac{dx}{dt} = -r \sin\theta \left[1 - \frac{r \cos\theta}{\sqrt{L^2 - r^2 \sin^2\theta}}\right] \frac{d\theta}{dt} \tag{6}$$

If the end of the rod B is placed against the center of the diaphragm of the pressure measuring instrument, the diaphragm center will be

deflected with a known velocity, and the consequent galvanometer deflection can be measured. Then

$$D = -k_1 r \sin\theta \left[1 - \frac{r\cos\theta}{\sqrt{L^2 - r^2\sin^2\theta}}\right]\frac{d\theta}{dt} \qquad (7)$$

By substituting known values of r, L, θ, D, and $\frac{d\theta}{dt}$ in equation (7) k_1 is determined. The value of θ at any point of the film record is known since the record made by the galvanometer during the calibration process is a periodic curve on a uniform time basis.

In order to determine k_2 it is simply necessary to make a pressure-deflection calibration of the diaphragm, using a dial gauge or micrometer to measure the deflections.

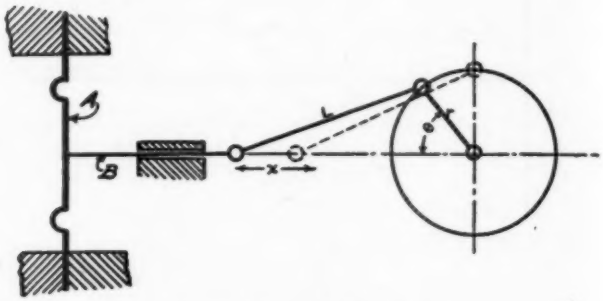

FIG. 3. *Calibrating Mechanism.*

Then, knowing k_1 and k_2, the recorded data from the galvanometer can be translated into a curve of pressure against time, with a scale of pressure definitely determined. By means of a mechanical integraph the pressure-time curve could be drawn directly and the pressure scale determined from the constants of the instrument as before.

In using the crank mechanism for calibration it is necessary to restrict the deflection x of the diaphragm center to a distance corresponding to the deflection attained with the maximum pressure it is desired to measure.

In conclusion the writer wishes to thank Professor Jakob Kunz of the Department of Physics for his suggestions.

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OPTICAL RATE-OF-CLIMB RECORDERS—THEIR USES, THEORY, AND DESCRIPTION*

By A. H. Mears and D. H. Strother

INTRODUCTION

The instruments described in this paper were developed by the staff of the Bureau of Standards at the request and with the financial assistance of the Air Service, U. S. Army, and the Bureau of Aeronautics, U. S. Navy.

Progress in aviation requires an exhaustive study of the characteristics of aircraft during flight. To enable an intelligent study of the behavior of the craft to be made, suitable instruments of high accuracy must be provided for test work in addition to the service instruments which are part of the standard equipment. In the design of an instrument the fundamental facts which must be taken into consideration are whether it is to be used as a flight test or a service instrument, and whether it is to be used on heavier-than-air or on lighter-than-air craft. On heavier-than-air machines the instrument must be of rugged construction to withstand successfully the vibrations of the airplane and the shocks of taxi-ing over the ground. Furthermore since an airplane does not necessarily fly level, the position error[1] must be reduced to a minimum. In lighter-than-air craft rate-of-climb instruments are not subjected to mechanical shocks, but must be extremely sensitive to overcome static friction in the moving parts. This is not necessary on heavier-than-air machines owing to the vibrations experienced.

There are other conditions encountered during flight which must be forseen. An instrument which gives perfect performance in the laboratory may be useless in flight owing to failure to anticipate all the conditions to which it may be subjected.

METHODS OF DETERMINING RATE OF CLIMB

An examination into the means available for determining rate of climb of aircraft will make clear the utility of a special instrument for measuring this quantity. The following are the methods which can be employed in the determination of rate of climb.

* Published by permission of the Director of the Bureau of Standards of the U. S. Department of Commerce.

[1] Position error is the change of reading of the instrument caused by tilting.

1. Observe the change of altitude between two levels as indicated on the altimeter and note by means of a stop watch the time interval elapsed. The accuracy of this determination depends upon selecting a good altimeter, making accurate readings, employing small altitude differences, and making proper corrections for instrumental errors. Altitude-time curves and rate-of-climb-time curves can be plotted from the data thus obtained. However this method requires the entire attention of an observer in addition to the pilot. If the rate of climb is computed during flight there is always a delay between the time when the records are taken and the time when the computations are made, which is obviously a disadvantage if the pilot has to use this information. This method is recommended only as a means of checking the accuracy of rate-of-climb instruments under flight conditions.

2. Compute the rate of climb from a chart of a barograph or altigraph having an open time scale. The same attention to the selection of the instrument and the correction of errors is required as in the first case. Greater accuracy can be obtained if the behavior of the instrument is known for various rates of climb. But this precaution need not be taken with instruments having small elastic errors which show a very small change of slope in their calibration curves even with widely varying rates of pressure change. Barographs using rectangular coordinate charts, such as are being developed at the Bureau of Standards, have the added advantage of giving greater accuracy in the rate-of-climb determination owing to the elimination of the curved time coordinates. These instruments also have extremely small elastic errors. The second method is the more desirable for performance testing since it does not require the attention of an observer in flight; but it does require considerable study of the instrument chart and the plotting of rate-of-climb-time curves. This method also is useless to a pilot during flight.

3. Time the frequency with which the bubble breaks on a bubble statoscope. This method at best is inaccurate and requires the complete attention of an additional observer. If complete data, such as obtained in the above methods are desired, additional observations of an altimeter are required.

4. Read the rate of climb directly from a rate-of-climb indicator. These readings inform the pilot or observer at once of the approximate rate of climb, without time observations or subsequent calculations. In addition, indications of variations in the rate of climb are given, which are practically unobtainable in the preceding methods. For the pilot's information during the flight this is the best means to obtain

rate of climb, but the securing of complete data requires the recording of the time of the readings and either additional observations of an altimeter or the use of a barograph.

5. Use a rate-of-climb recorder. This has the advantage of not requiring the attention of an observer and, while a direct reading is not available to the pilot, its use with an accurate barograph or altigraph gives all the information desired. The chart of the rate-of-climb recorder also shows very clearly all the variations in the rate of climb during the flight. The lack of equilibrium in the free air is also shown very clearly. A reproduction of an actual record of a flight is shown below in Fig. 1.

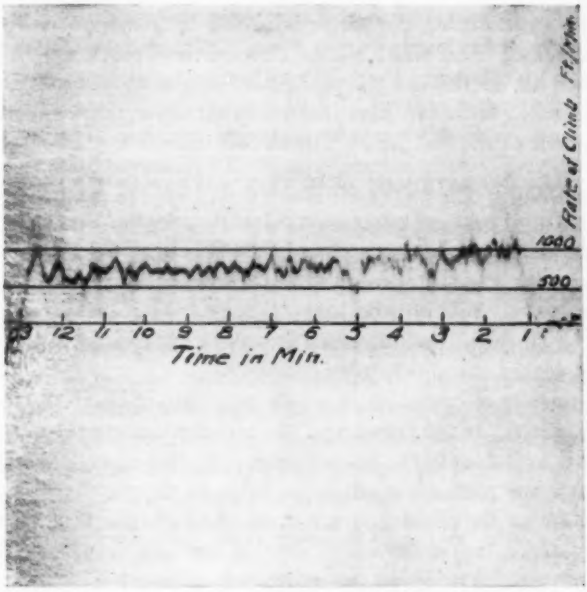

FIG. 1. *Flight record of rate-of-climb recorder.*

USES OF RATE-OF-CLIMB INSTRUMENTS

On heavier-than-air machines both indicating and recording rate-of-climb instruments are used most extensively in performance testing and have practically no use as service instruments. On lighter-than-air craft, however, the rate-of-climb indicator is almost invaluable for service purposes, for it is the instrument upon which the navigating

officer depends principally when landing or weighing off. For this use an extremely sensitive instrument is required and an error of a few feet per minute in the rate-of-climb indication of the instrument would jeopardize the safety of the passengers and crew, to say nothing of the waste of ballast or of the inflating gases.

In the performance testing of aircraft[2] one of the characteristics determined is the climbing speed of the ship. For this purpose the rate-of-climb indicator has the advantage that the pilot, in order to obtain his maximum climbing speed, has only to manipulate the controls so as to secure the maximum indication of the instrument. The use of a rate-of-climb recorder in conjunction with an indicating instrument enables the test pilot to collect information of the greatest importance concerning the performance of the machine with the least possible mental effort on his part. This fact is of much weight since by using such an instrument the pilot can focus most of his attention on other matters. It was to meet this need that the authors undertook the development of the instruments described later.

PRINCIPLE OF OPERATION OF LEAK TYPE RATE-OF-CLIMB INSTRUMENTS

The essential parts of a rate-of-climb instrument of the leak type are: (1) a thermally-insulated air chamber which is closed to the external air, except for a small opening or leak which may consist of either a needle valve or capillary tube; and (2) some kind of pressure indicating device, which shows the difference in pressure between the external air and that within the air chamber.

The principle of operation of a leak type rate-of-climb instrument is a simple matter. If the pressure of the air surrounding the air chamber is varying, as it does in the case of aircraft having a vertical component of velocity, the pressure equilibrium between the air chamber and the external air is disturbed and air flows through the leak device, the direction depending upon which side of the leak is subjected to the excess pressure. Owing to the resistance offered by the leak device, as long as the air is flowing through the leak, there is a pressure difference between its two ends.

The pressure difference is measured by some type of pressure indicator and the magnitude of this difference, as will be seen later, is a measure of the rate of climb. Either a liquid manometer or the deflection of a sensitive diaphragm is used for this purpose.

[2] T. M. Barlow, "Performance Testing of Aircraft," The Aeronautical Journal, *26*, No. 137, p. 158.

In order that the instrument may function properly the flow of air through the leak device must be non-turbulent. Since such a flow depends upon the viscosity of the air, and since the viscosity of a gas is independent of its density, it can easily be proved that an instrument constructed on this principle and graduated to indicate rate of climb will have a scale value[3] which will be approximately independent of the altitude as determined by pressure. The mathematical proof of this fact will be undertaken later in the paper.

LIQUID AND MECHANICAL RATE-OF-CLIMB INDICATORS

Leak type rate-of-climb indicators can be divided into two general classes, liquid and mechanical according to whether a manometer tube or a flexible diaphragm with a mechanical indicating mechanism is used with the air chamber. The liquid rate-of-climb indicator is possibly slightly more sensitive to small variations of pressure, but it has some great disadvantages: (1) it must be held level in order that the liquid manometer may indicate the true pressure difference, and that the liquid may not be spilled; (2) the evaporation of the liquid changes the zero reading; (3) at very low temperatures the liquid is liable to become viscous; and (4) if bubbles are introduced into the system through tipping, the instrument becomes valueless as far as an accurate reading is concerned.

Because of the inherent disadvantages of the liquid rate-of-climb indicators the Bureau of Standards recording instruments are equipped with a flexible metallic mechanism as the actuating pressure element.

The pressure element of a mechanical rate-of-climb indicator consists essentially of a cylindrical air chamber connected to the external air by a capillary tube and having a flexible member which usually consists of a thin metallic diaphragm across the top.

THEORY OF LEAK TYPE RATE-OF-CLIMB INSTRUMENTS

The theory of the rate-of-climb instruments with leak devices producing non-turbulent flow, under conditions of constant rate of change of altitude and in an isothermal air column free from atmospheric circulation, is easily understood. Let us consider that the volume of the air chamber remains constant and that the mass of the air within the chamber varies at the same rate as would the mass of an equal volume

[3] The scale value of a rate-of-climb instrument is here defined as the ratio of the rate-of-climb as determined by pressure measurements to the rate-of-climb indicated by the instrument.

of free air subjected to the same rate of altitude change. That this last assumption is very nearly true is borne out by laboratory tests of correctly designed leak type instruments under artificial atmospheric conditions closely approximating the conditions assumed. Naturally the ideal conditions of the external atmosphere as assumed above only approximately prevail, but the assumption is justified for a clear short exposition of the theory. A discussion involving varying temperature and circulation of the atmosphere would lead to intricate equations which are not necessary for grasping the simple and important fact that the scale value of a rate-of-climb instrument is independent of altitude.

The next point to be considered is the law of the flow of a gas through a capillary tube or its equivalent, which will give a value for the rate of change of the mass of the air within the chamber if the pressure difference between the two ends of the capillary is known. In the present discussion this pressure difference is assumed to be equal to the difference in pressure between the external atmosphere and that of the air within the air chamber. The law for such a flow of a gas through a capillary was stated by Poiseuille and is given below under the mathematical treatment of the theory. In connection with this law the experimental fact that the coefficient of viscosity of a gas is independent of the pressure must be kept in mind because it is for this reason that the scale value is independent of the altitude for the ranges of pressure and altitude appertaining to aircraft performance.

If the expression, derived from Poiseuille's law for the rate of change of the mass of air within the air chamber for a pressure difference between the ends of the capillary be equated to an expression derived from the isothermal pressure-altitude relation for the rate of change of mass of a volume of free air equal to that enclosed within the air chamber, it will be seen that in the resulting equation the pressure terms cancel out. As a result of this fact the rate of change of isothermal altitude is proportional to the pressure difference developed between the two ends of the capillary tube and is independent of the pressure on the system—in other words, of the altitude at which the instrument is functioning.

Let m_0 be the mass of a quantity of free air equal in volume to that enclosed within the air chamber of the rate-of-climb instrument under consideration which is at an isothermal altitude level Z_0 and at the corresponding pressure p_0, and let m be the mass of the same volume of

free air at an isothermal altitude level Z and at the corresponding pressure p.

From the pressure-altitude relation

$$Z = 62900 \log_{10} \frac{759.6}{p},$$

or

$$Z = 181189 - 62900 \log_{10} p, \tag{1}$$

where Z is the isothermal altitude in feet and p is the corresponding pressure in millimeters of mercury. Differentiating (1) with respect to time

$$\frac{dZ}{dt} = -K \frac{1}{p} \frac{dp}{dt} \tag{2}$$

where K involves the constant in the formula and takes into consideration the modulus of logarithms.

Since the volume and temperature of the air under consideration remain constant we can write

$$m = \frac{m_0 p}{p_0}, \tag{3}$$

where m_0 is the mass of a volume of air at an isothermal altitude Z_0 and corresponding pressure p_0 and m is the mass of the same volume of air at an isothermal altitude Z and the corresponding pressure p. Differentiating (3),

$$\frac{dm}{dt} = \frac{m_0}{p_0} \frac{dp}{dt}. \tag{4}$$

Solving for $\frac{dp}{dt}$,

$$\frac{dp}{dt} = \frac{p_0}{m_0} \frac{dm}{dt}. \tag{5}$$

Substituting in equation (2) and writing K_1 for $K \frac{p_0}{m_0}$,

$$\frac{dZ}{dt} = -K_1 \frac{1}{p} \frac{dm}{dt}$$

or

$$\frac{dm}{dt} = -\frac{p}{K_1} \frac{dZ}{dt}. \tag{6}$$

Now writing the derived form of Poiseuille's law:

$$\frac{dm}{dt} = \frac{\rho_0 p \pi r^4 \Delta p}{8 p_0 l \mu}, \tag{7}$$

where $\frac{dm}{dt}$ is the rate of change of the mass of air in the air chamber assumed equal to the rate of change of mass of an equal volume of free air,

ρ_0 is the density of the air in the air chamber at an isothermal altitude Z_0 and a corresponding pressure p_0,

p is the pressure on the system or free air pressure at the corresponding isothermal altitude Z,

r is the radius of the capillary leak tube,

Δp is the pressure difference between the two ends of the capillary and is assumed to be equal to the difference of pressure between the free air and that in the air chamber (if p_i is the pressure of the enclosed air $\Delta p = p - p_i$), l is the length of the capillary, and μ is the coefficient of viscosity of the air at the given temperature. Equating (1) and (7)

$$-\frac{p}{K_1}\frac{dZ}{dt}=\frac{\rho_0}{p_0}\frac{p\pi r^4}{8l\mu}\Delta p.$$

Cancelling the p's and rewriting:

$$\frac{dZ}{dt}=-\left[\frac{K_1\rho_0}{p_0}\frac{\pi r^4}{8l\mu}\right]\Delta p, \tag{8}$$

where all the terms inside the brackets are independent of the pressure or altitude.

DEVELOPMENT OF BUREAU OF STANDARDS RATE-OF-CLIMB RECORDERS

The first of these instruments as originally designed was composed of a pressure element, affected by rate of altitude change, and a recording element, by which the record on a chart was made. The pressure element consisted of a "sylphon" diaphragm, which was closed to the external air except for communication through a capillary leak tube. The sylphon diaphragm consists of a corrugated cylindrical tube of very thin metal. In this case a brass tube with annular corrugations was used. The thickness of the metal was about 0.0035 inches. The plates attached to the top and bottom of the tube were of rigid construction, thus forming an air chamber whose action resembled that of an accordion. A glass capillary tube was used 10 cm long and 0.08 cm internal diameter.

The sylphon was used because it gave a greater deflection than could be obtained with a metallic diaphragm and air chamber of equal size.

In considering this instrument it was first thought that the flexible member could be connected by suitable levers to a pen which would record on a paper chart. Experiments soon showed that this would not be practical. The main difficulties encountered were due to the weight of the lever arm, which gave an added amount of inertia to the system, and the friction between the pen and the paper chart. In a rate-of-

climb instrument it must be remembered that the power developed by the pressure changes is a very small quantity and therefore the mechanism attached to the flexible sylphon must be as light and as nearly frictionless as possible. The only solution seemed to be an optically recording instrument.

The first device tried was a tube containing a 2 volt flash light bulb mounted on the end of a sylphon. The bulb was mounted in a cylinder in front of which was placed a converging lens. The focus was adjusted by turning the thumbscrew (a) shown in Fig. 2. This slid the cylinder which contained the lamp backward or forward in the outer cylinder

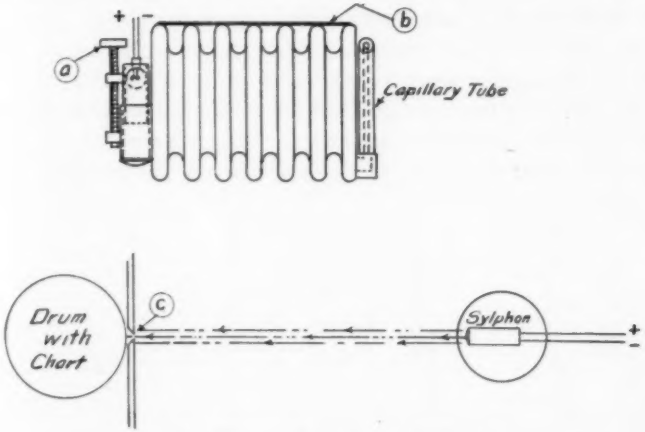

FIG. 2. *Diagram of experimental mechanism.*

which was anchored on the sylphon and to which the lens was attached. A piece of wire (b) was soldered to one side of the sylphon so that the length of this side was kept constant, and when the other side of the sylphon expanded or contracted, the ray of light from the electric bulb was turned through an angle the magnitude of which depended upon the pressure difference between the inside of the sylphon and the external atmosphere.

The image of the filament was thrown on a sheet with a narrow horizontal slit (c-Fig. 2) so that only a point of light fell on the sheet of bromide paper carried by a revolving drum. A trace was obtained, but the definition was poor and stray light effects were visible on the paper. It was thought better to use a straight filament lamp rather than the ordinary "S"-shaped type so that any portion of the filament might be

used as the image instead of a single portion which was necessary with the "S"-shaped image.

The method of anchoring the light source on the end of the sylphon proved unsatisfactory as the excessive weight of the light casing gave a large position error. The next step was to mount the bulb beneath the drum directing the light toward a mirror mounted on a shaft rotated by the sylphon. The rays were thus reflected by the mirror back to the slit and to the drum. Again stray light effects were very noticeable and the image itself was too large for any precision measurements.

BUREAU OF STANDARDS RATE-OF-CLIMB RECORDER NO. 1

In the Bureau of Standards Rate-of-Climb Recorder No. 1, which was developed for the Bureau of Aeronautics, United States Navy, the light path was enclosed as much as possible in order to eliminate stray light effects. Also, to improve the definition of the image of the filament, a lens of long focal length was employed. The optical system can best be studied by referring to Fig. 3. A six volt single filament galvanometer

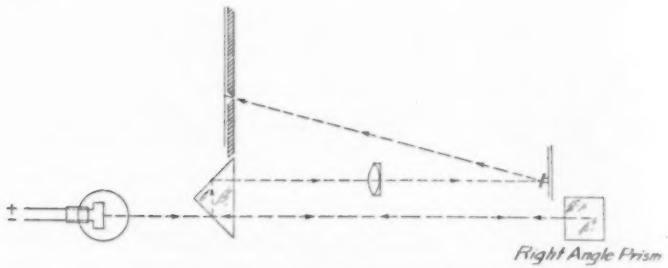

FIG. 3. *Optical system of first model.*

lamp was placed in a tube the inside of which was painted with an optical black. A right angle prism was placed at the end of the tube which reversed the direction of the light path and sent it through a second tube. Another prism was placed at the other end of the second tube which again reversed the direction of the light path. From this point it was projected through a lens to a small plane mirror mounted on a vertical shaft rotated by the sylphon. This mirror threw the image of the filament on a straight line horizontal knife-edge slit and gave a point of light on the recording drum. Thus a good clear trace was obtained on either film or bromide paper. During this phase of the development Mr. A. F. Eckel of the Bureau of Standards gave many

valuable suggestions and aided materially in the success of the recording device.

Although this model in its experimental stage performed satisfactorily in the laboratory, when it was taken on flight tests the trace obtained was blurred and indefinite. This was found to be due to two causes. One was that the vibrations of the plane caused vibrations in the sylphon which were transferred to the mirror and also caused the point of light on the drum to oscillate rapidly and spoil the trace. At the suggestion of Mr. F. Cordero of this Bureau these vibrational effects were stopped by putting a "U" shaped spring on the end of the sylphon, which offered slight resistance to longitudinal motion but effectually stopped all lateral vibrations. The second reason for blurring of the record was found to be due to the condensation of moisture on the

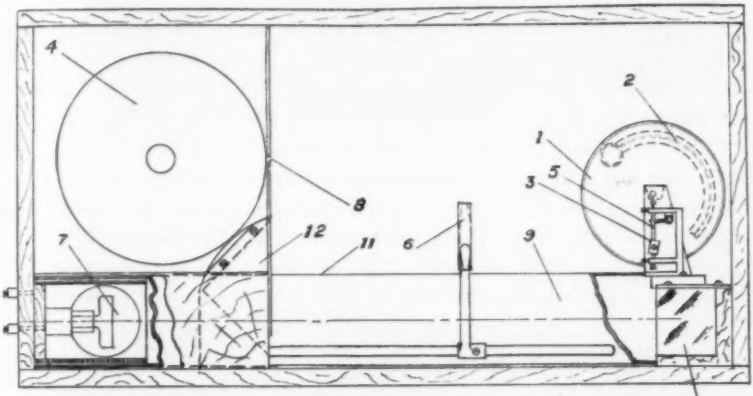

FIG. 4. *Diagram of first model.*

surfaces of the prisms and lens when the low temperatures at high altitudes were reached. This was remedied by attaching to the inside of the case a tube filled with calcium chloride, which kept the air sufficiently dry for a satisfactory record to be obtained.

Referring to Fig. 4 the operation of the instrument is as follows:

When the pressure on the instrument remains constant, the pressure within the air chamber (1) and the external pressure are equal, owing to communication through the leak device (2). The mirror (3) will then cast a spot of light on the sensitized chart mounted on the clock-work-driven drum (4) of the instrument, and this determines the zero of the rate-of-climb record as there is no deflection of the air container

no matter what the actual pressure may be at that instant. If the pressure of the external air is changing at a given rate, as when the aircraft is ascending or descending, the pressure inside the air container will lag behind that of the external air owing to the resistance offered to the equalization of pressure by the leak device. This creates a pressure difference which causes the air chamber (1) to expand or contract according to whether the external air pressure is decreasing or increasing. This expansion or contraction causes a displacement of the top of the sylphon along a line perpendicular to its surface. The movement causes a rotation of the mirror (3) by means of its connection to the top of the sylphon through a system of levers.

The mirror (3) is mounted on the shaft (5) so that the plane of its surface makes an angle of approximately 15° with the shaft (5). In this manner the reflected beam from the mirror will clear the lens (6) and throw the image of the filament of the lamp (7) on the slit (8). The rotation of the mirror (3) causes a deflection of the image of the filament of the light (7) along the slit (8) and therefore of the spot of light falling on the light-sensitive chart attached to the revolving drum (4).

The light from the lamp (7) whose filament is a fine straight wire and therefore gives a line beam of light, travels through the tube (9), and is reversed in direction by the total reflecting prism (10) and travels through the tube (11). Here it is again reversed by the total reflecting prism (12), passes through the lens (6) and falls on the mirror (3), where it is reflected to the slit (8) and falls on the sensitized chart. The lens (6) is adjusted to such a position that the image is in focus on the light-sensitive chart carried on drum (4). The lamp (7) is mounted so that the line image of its filament will be at right angles to the slit (8). The motion of the drum (4) in combination with the movement of the spot of light on it produces a continuous record of the rate of climb when the light-sensitive chart is developed.

This instrument, while proving satisfactory, was built primarily as an experimental model. It is shown in Figs. 5 and 6.

BUREAU OF STANDARDS RATE-OF-CLIMB RECORDER MODEL NO. 2

The Bureau of Standards Rate-of-Climb Recorder Model No. 2, which is shown in Fig. 7, was built for the Engineering Division of the United States Army Air Service and has several refinements not contained in the previous model.

Instead of having a drum the new instrument employs a continuous film, rolling off one spool onto another, and thus gives a much more

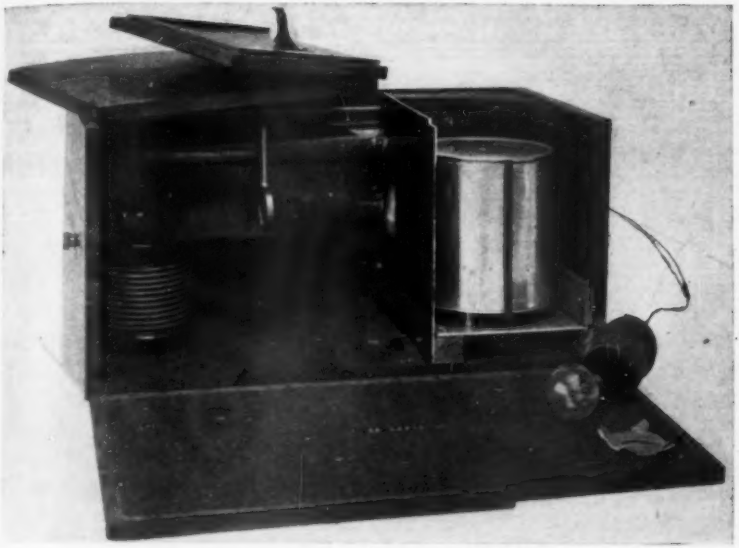

FIG. 5. *First model of rate-of-climb recorder.*

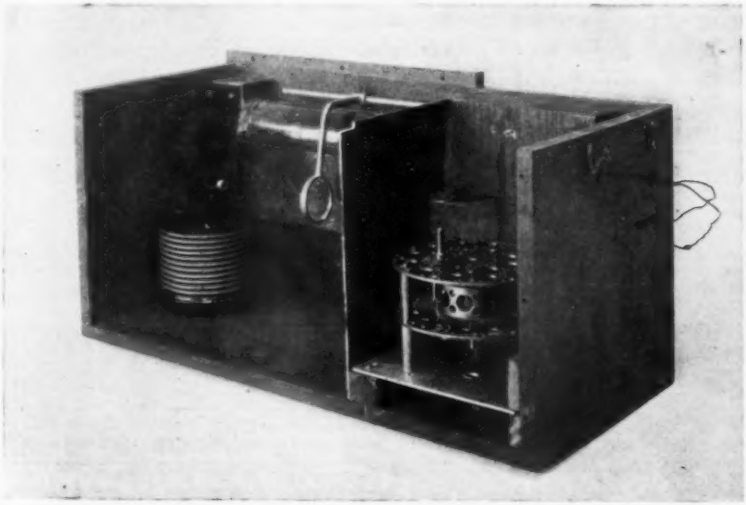

FIG. 6. *First model of rate-of-climb recorder.*

open time scale and longer record than was possible with the drum. An aluminum case was used instead of a wooden one in order to render the instrument more nearly light-proof. This increased the weight but added to its strength and ruggedness. In the first model an external six volt source was necessary to operate the lamp. In the second model two flashlight cells were contained inside the case and gave sufficient wattage to operate successfully the 2.5 volt single filament flashlight lamp that was used.

Some trouble was experienced in obtaining a lamp that did not give a double image. If the filament was not exactly in the center of the bulb or if the bulb was not perfectly round, a double image was thrown on the chart. Out of twenty-four lamps ordered only four were found that did not give a double image.

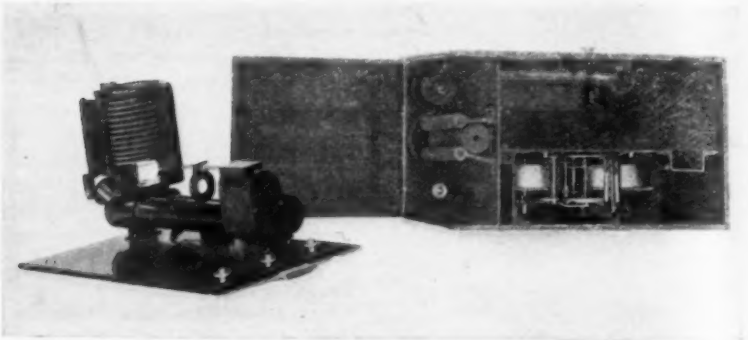

FIG. 7. *Second model of rate-of-climb recorder.*

Another point was the addition of a red glass window through which the spot of light could be observed and the movements of the spot up and down the scale could be watched. This proved very useful in testing, as much time was wasted in making a lengthy record with the earlier instrument when it was not functioning properly, and there was no means of discovering this except by removing the instrument to a darkroom and developing the trace.

The drive for the record rollers in this instrument is a clock mechanism with a centrifugal governor. A knob was constructed on the outside of the case so that the clockwork could be started and stopped at the will of the observer.

The speed of the roller drive can be changed so that the openness of the time abscissa can be varied to suit the nature of the test. The instrument can be used with a timer, which with the introduction of an extra lamp flashes a light at minute intervals so as to give a time line on the record.

Some trouble was still experienced in overcoming stray light effects. The reflections along the tubes gave ghost lines on the record and several of these false images were formed because of reflections from different surfaces. It was found necessary to place diaphragms at intervals along the tubes, and also to reduce the size of the aperture of the lens by means of a diaphragm before a good clear image of the filament was obtained.

On the final test the instrument gave an excellent record and one on which the scale was sufficiently open to give small changes in rate of climb. The authors were fortunate in having the assistance of Mr. C. R. Letzkus of this Bureau in the construction of these instruments. He offered many valuable suggestions and a number of his ideas are incorporated in both instruments.

BUREAU OF STANDARDS,
WASHINGTON, D. C.

Measurements of the Ionization and Resonance Potentials of Neon and Argon by New Methods.—Hertz locates the resonance potentials of Ne and Ar by a modification of the four-electrode apparatus, in which there is an electron-accelerating voltage between filament and first grid, a wide equipotential region between first and second grid and an electron-retarding voltage of 0.2 between second grid and plate. In his modification the first and second grids are united to form a box, and the electrons reaching the plate are those which leave the box at right angles to the direction of entrance. Measurements of plate current are made alternately with the retarding voltage on and off; the difference gives the number of electrons escaping from the box with less than 0.2 volt energy, which are numerous only in the very close neighborhood of a resonance potential; the curves therefore show sharp maxima at each resonance potential. This method cannot be used to locate ionization potentials, apparently because the detached electrons have less than 0.2 volt speed even when the impinging electrons have much more than the ionizing energy, and also because the efficiency of ionization increases rapidly as the excess of their energy over the ionizing energy increases. To find the ionizing potentials a new filament is introduced into the box and heated to so high a temperature that its electron emission is limited by space charge. The voltage of the electrons entering the box from the first filament is then raised until the emission from the second filament is suddenly increased by

the appearance of positive ions in the gas. A mixture of helium and neon is used so as to calibrate the voltage scale by locating the resonance potentials of He. Setting the lower of these at 19.75 volts, the resonance potentials of Ne are found to be 16.65 and 18.45 volts, the ionizing potential at 21.5 volts; the resonance potentials of A are at 11.55 and 13.0 and 14.0 volts, its ionizing potential at 15.3 volts.

The value 21.5 volts for neon fixes the value of the ($1s$) term, not heretofore detected by optical means. The value 16.65 volts agrees well with the difference between this and the $2s$ terms which have been detected by spectrum analysis, and the value of 18.45 volts agrees well with the difference between this and the $2p$ terms. The several $2s$ and the several $2p$ terms form two groups much too close to be resolved by the electron impact method; but Hertz was able to show that the line 5852, emitted when an electron falls inward from one of the outermost of the various $2p$ levels, requires an appreciably more violent electron impact to produce it than certain lines in which the electron starts from one of the inner $2p$-levels. The value 15.3 volts for argon also presumably fixes its $1s$ term, but the spectrum analysis of the higher terms has not yet been made. [G. Hertz (Eindhoven); ZS. f. Phys. *18*, pp. 307-316; 1923]. K. K. DARROW

Gift of Optical Apparatus and Machinery.—The Bausch and Lomb Optical Company of Rochester, N. Y. has recently presented to the Department of Physics in Columbia University a handsome collection of optical apparatus and machinery, for instruction and research, particularly in applied optics, optometry and physiological optics. On February 29 an exhibition of the apparatus was held in Fayerweather Hall. Mr. Adolph Lomb himself was present and also Mr. Max Poser of the Bausch and Lomb Optical Company. President Butler accepted the gift on behalf of the trustees of the University, and Dr. Herbert E. Ives, President of the Optical Society of America, delivered an address on Modern Progress in Physiological Optics.

Gold Medal Awarded to William Gaertner.—Mr. Wm. Gaertner, President of The Gaertner Scientific Corporation, Chicago, has been awarded the Howard N. Pott's Gold Medal by the Franklin Institute "in consideration of his notable achievements as a designer and maker of scientific instruments, materially contributing to success of the research in physical science."

Mr. Gaertner was, for twenty-eight years, the proprieter of Wm. Gaertner and Company, makers of scientific instruments, and he is now the head of The Gaertner Scientific Corporation. He is recognized as one of the leading scientific instrument makers in the United States, and has supported heartily the movement toward making educational and scientific institutions in America independent of foreign made instruments.

A COMBINED ILLUMINOMETER AND REFLECTOMETER

By G. A. Shook

This instrument is essentially an illuminometer and may be used like any illuminometer but it is so designed that when used in connection with an integrating sphere it becomes a portable reflectometer. As such it has the advantage that only one source of current is required and moreover no ammeter or rheostat is necessary. The comparison lamp of the illuminometer furnishes the illumination for the sphere and as the current for this lamp may be obtained from a small flash light battery attached to the sphere, no auxiliary apparatus is required when the instrument is used as a reflectometer. It is therefore very convenient for measuring the reflection factors of walls etc.

Fig. 1 shows the illuminometer *I* and the sphere *S* separate and also the two combined.

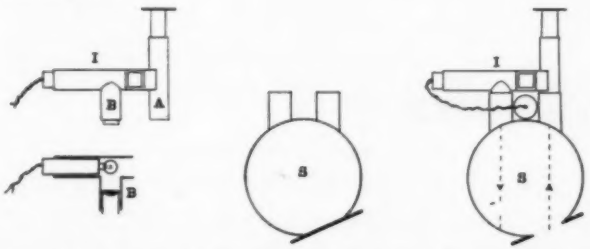

Fig. 1. *General arrangement of illuminometer and sphere. The illuminometer can be readily attached to the sphere.*

The flux to be measured passes up through the tube *A* and is compared photometrically with the lamp in the instrument. Light from the same lamp passes down through the tube *B* and may be used to illuminate a small portion of the sphere wall. The beam is rendered parallel by means of a lens in *B* as shown.

When used as an illuminometer the instrument is connected to a case containing three dry cells, an ammeter and a rheostat. As a reflectometer the current may be obtained from an attached battery as indicated or from any other source.

The instrument as now used by the writer does not give the absolute value of the reflection factor as in the case of the reflectometer recently

described by Taylor[1] although it might be arranged to do so with some modifications. A magnesium carbonate block[2] is used as a standard and as it reflects very nearly 100% its reflection factor may be taken as 1 for approximate results.

In the design of optical apparatus the problem of varying the intensity of light in a continuous and determinate manner is one that presents itself about as often as any other. For simple pieces of apparatus the author has found the neutral tint wedge the most satisfactory as it may be easily mounted in telescope tubing of square cross-section and moreover wedges may be obtained in a variety of

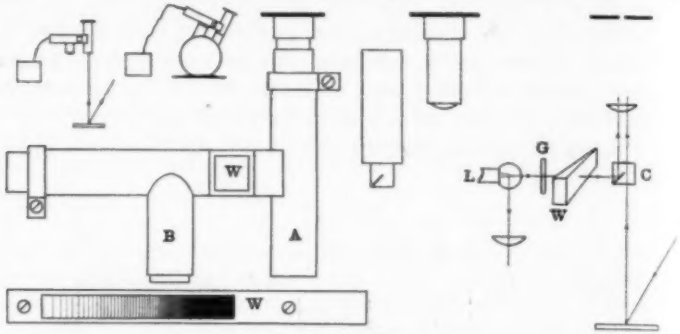

FIG. 2. *Details of the illuminometer.*

ranges. To measure the illumination then at any point it is only necessary to compare the brightness of a standard matt surface, placed at the point, with the brightness of the diffusing glass in front of the lamp in the instrument. The apparent brightness of the diffusing glass may be varied by means of a wedge.

Fig. 2 shows some of the details of construction as well as the optical system. The instrument lamp L is a 3.8 volt flash light bulb and is mounted in an adjustable tube so that it may be readily brought to the proper position with respect to the lens system in tube B. The light is diffused by means of an opal glass, G.

The wedge W which cuts down the light of L, is mounted in a telescope tube $8 \times \frac{1}{2} \times \frac{1}{2}''$ and this tube fits into the next size larger. A cen-

[1] Bureau of Standards Sci. Paper, No. 405.
A simple portable instrument for the absolute measurement of reflection and transmission factors.

[2] A. H. Taylor, Bureau of Standards Sci. Pap. No. 391.
Trans. Ill. Eng. Soc. *15*, p. 811, 1920.
C. H. Sharp and W. F. Little, Trans. Ill. Eng. Soc. *15*, p. 802, 1920.
E. Karrer, Bureau of Standards Sci. Pap. No. 415

timeter scale is placed on the upper side of the tube as well as a foot-candle scale. The adjustment of the cube C is simplified by mounting it on the end of the eye piece tube as it may then be raised, lowered or rotated about the axis of the instrument.

The wedge used here is 10cm long and so constructed that at any point the density is proportional to the distance from one end and the density is defined as the logarithm of the reciprocal of the transmission. The upper limit of the scale will depend upon the intensity of the lamp and how far it is from the diffusing screen. With arrangement described an illumination up to 25 foot-candles can be measured. The lower limit will depend upon the maximum density of the wedge.

In order to determine reflection factors, one proceeds as follows:

Suppose a surface of reflection factor ρ_1 covers the open portion of the sphere when a balance is made and let the reading be R_1. If the brightness of the diffusing glass is B_0 and the illumination falling upon the surface is B, then from the law of the wedge

$$\log \frac{B_0}{\rho_1 B} = nR_1$$

For any other surface of reflection factor ρ_2

$$\log \frac{B_0}{\rho_2 B} = nR_2$$

whence

$$\log \frac{\rho_1}{\rho_2} = n(R_2 - R_1)$$

When a magnesium carbonate block is used ρ_1 may be taken as 1.

When R is in centimeters the constant n is equal to 0.1 for a wedge of maximum density 1 or it is equal to 0.2 for a wedge of density 2 etc.

The method of calibrating the illuminometer is obvious.

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A New Electromagnet.—This electromagnet is built in the same general manner as that of Ruhmkorff, with an iron yoke in the form of a frame or U, with iron cores extending transversely inwards from the tops of the arms of the U and carrying the magnetizing coils. The designers apparently lay greatest stress on the following features: the magnetizing coils are air-cooled instead of water-cooled, the cooling being performed by an electric fan mounted on the bottom cross-piece of the yoke, and facilitated by the manner of winding the magnetizing coils, each of which consists of several plane spirals with 80 windings apiece, connected in series and separated by air-spaces. The cores taper

slightly towards their ends, on which the conical pole-pieces are mounted; the induction is made as large and the magnetic leakage as small as possible at the junction of core and pole-piece (by reducing the radial distance from surface of core to innermost windings of coils, and the lateral distance from outer end of coil to outer end of core). No unprecedently large field is produced; the claim made for the instrument is that fields of the order of 30,000-50,000 gauss can be maintained for hours at a time, without overheating or the need of water-cooling, and with a sensibly smaller total mass of iron. The method of measuring the field-strength between the pole-pieces is described with superfluous detail. It appears that a field of 25,000 gauss can be obtained with cylindrical flat-faced pole-pieces 84 mm in diameter and 7 mm apart, and is sensibly uniform over a region of some two-thirds this diameter; while a field of 48,000 gauss can be obtained with conical pole-pieces tapering at a 60° angle down to faces 10 mm in diameter and 1 mm apart. These fields are obtained with currents of 25 amperes and power expenditure of 3.4 kw.—[H. Boas & T. Pederzani, Berlin; ZS. f. Phys. *19*, pp. 351-374; 1923].

KARL K. DARROW

Relation between Number of Quanta absorbed and Number of Quanta emitted when X-rays fall upon Atoms.—After describing a number of experiments which might be performed either to find this relation, or to measure the intensity of an x-ray beam by assuming some form for it, Kossel examines data published by Sadler in 1911 upon the intensities of fluorescent x-rays excited by primary x-rays of measured frequency and intensity, incident upon plates of Cr, Fe, Co, Cu, and Zn. The frequencies of the primary rays were greater than the K-frequency of the metal. The measurements were actually made upon the ionization produced by these rays in an ionization chamber. To reduce those to intensity measurements, Kossel assumes that when rays of frequency ν are absorbed in an ionization-chamber they produce electrons of energy $W = h\nu$, which in turn produce a total number of ions given as a function of W by Lenard's experiments on total ionization versus initial speed for fast electrons. The ionization currents are therefore to be multiplied by a factor depending on ν in order to get values proportional to the intensity of the x-rays. Doing this Kossel finds that Sadler's data show that the ratio (number of quanta of secondary radiation emitted): (number of quanta of primary radiation incident) is independent of ν, being 0.23 for Cr, 0.32 for Fe, 0.39 for Co, 0.42 for Cu, and 0.51 for Zn. The constancy of the ratio in any particular case is more reliably assured than the absolute value given.—[W. Kossel, Kiel; ZS. f. Phys. *19*, pp. 333-346; 1923].

KARL K. DARROW

A REVOLVING MIRROR FOR USE WITH THE STRING GALVANOMETER

By A. Forbes and David W. Mann*

The usual method of observing results with the string galvanometer is photographic recording. The photographing plate, film, or bromide paper is moved behind an illuminated slit through which the beam of light from the galvanometer is usually concentrated in a sharp line by means of a cylindrical lens. The sharp line thus projected on the photographing surface is perpendicular to the string, and the film or plate is made to move at a uniform velocity in a direction perpendicular to the illuminated slit (i.e. parallel to the string). In this way the excursions of the string in the galvanometer are recorded as a curve in which the abscissae represent time, and the ordinates, deflection of the string caused by current applied thereto. This method of recording necessitates developing the plate, film or paper before the results can be examined.

For some purposes it is highly desirable to observe the excursions of the string as they occur. It is possible by simply throwing the shadow of the string on the screen to observe whether deflections are occurring or not, except in the case of very small and very brief excursions; but in the case of the great majority of rapid excursions for which the string galvanometer is especially useful, it is impossible to observe the time relations of the deflection, that is, to see the shape of the curve which would result if these were recorded photographically. For several purposes it is desirable to observe the time relations of the deflections as they occur. In particular, this need is felt in the case of many researches in nerve physiology. The action current or electric response occurring in the nerves of vertebrates when stimulated is a familiar phenomenon. With the exception of the minute evolution of carbon dioxide, it is the only direct, objective evidence of functional activity in a nerve trunk. It is the only direct index whereby accurate information about individual nerve impulses can be obtained. It is thus in many ways the principal key to nerve physiology. In the case of a medullated nerve at ordinary room temperature, e.g., 20° C., it has been shown that the action current reaches its maximum in less than 0.001 sec., and that the total duration of this phenomenon is only

* The actual construction of the apparatus was carried out by the second named author.

about 0.004 sec.[1,2] It is obviously too brief to permit the unaided eye to follow its time relations accurately.

In a recent research in these laboratories dealing with the refractory period of nerve,[3] it was necessary to record a series of action currents with stimuli of various strengths and then develop the film and examine it before proceeding with the experiment. The reason for this was that in a study of refractory phase it is essential that the first stimulus should be maximal, that is, should excite all the fibers in the nerve. Otherwise confusion may result from the second stimulus exciting fibers which failed to respond to the first. It is desirable not to use a much stronger stimulus than is necessary to produce a maximal response, since excessive increase in the strength of stimulus causes excitation at a distance from the stimulating electrode, and this might tend to confuse the resulting measurement of the refractory phase; also the electric artefact resulting from excessively strong stimulation may be extremely confusing in string galvanometer records.[4] In order, therefore, to determine the proper strength of the first stimulus it was necessary to take a series of records. This involved a delay of about half an hour in conducting the experiment. A clear picture of the response as it occurred would have obviated this delay. Again, in such an experiment as this there is so much uncertainty as to the duration of the refractory phase, that if one wishes to be sure of recording the earliest possible second response and a series of others at all stages of recovery of the nerve, it may be necessary to take a considerable number of photographic records with the two stimuli spaced at various intervals, over a wide range including many shorter and many longer than those desired, in order to be sure of including the important ones. This involves a considerable waste of time and film. Instantaneous viewing of the response would obviate this and enable the investigator to choose the desired interval at the outset, and then make only as many photographic records as he needed for further detailed study.

There are some researches in which for the majority of experiments the mere viewing of the response when it occurred would suffice, and no permanent photographic record would be needed. In such a research the saving of time and photographic material by a device which would render that possible is obvious.

[1] Adrian: Journ. Physiol., *55*, p. 193; 1921.
[2] Gasser and Erlanger: Amer. Journ. Physiol., *62*, p. 516; 1922.
[3] Forbes, Griffith and Ray: Amer. Journ. Physiol., *66*, pp. 553-617; 1923.
[4] Forbes and Gregg: Amer. Journ. Physiol., *39*, p. 185; 1915.

Apart from research, a notable use of such an apparatus would be the demonstration of action currents to classes of physiology. The sight of a response as it occurs would be more effective didactically than a photographic record made and exhibited to the class afterward.

Fortunately, there is a property of nerve which renders its function peculiarly suited to the desired form of observation. In order to obtain a clear picture of a curve representing the course of a brief event such as the electric response of nerve, it is necessary that it should be repeated over and over again with a frequency sufficient to produce visual fusion. It is a classical observation that a nerve trunk can be stimulated repeatedly 40 or 50 times a second over a long period of time without giving appreciable evidence of fatigue. This fact has been utilized by Gasser and Erlanger in the study of the action current of nerves with the Braun tube.[2] Their apparatus is undoubtedly the best that has yet been developed for this purpose. Unfortunately, this constitutes, particularly when the necessary amplifiers are included, a rather elaborate and expensive assemblage of apparatus. The string galvanometer, which is now in use in many laboratories, will record the action currents of an ordinary nerve without the aid of electron-tube amplification. With a string galvanometer already installed, it only needs the introduction of a comparatively simple device to render the action current of a nerve available for direct and immediate observation. A device for doing this has already been furnished as an accessory to the Edelmann galvanometer. We have developed for use in these laboratories another device, similar to the Edelmann apparatus in its basic principle, but differing from it in the way in which this principle is applied. It is our purpose to describe this device.

The essential principle is to produce on a screen uniform motion of the shadow of the string in the galvanometer in a direction corresponding to that in which the film moves in the recording camera; that is, perpendicular to the excursions of the shadow. The shadow of the string must repeat its excursions with sufficient frequency to produce good visual fusion,—a frequency which, as is well known from experience with motion pictures, must be at least 12 a second. To give the shadow of the string sharp definition in both dimensions it must not only be focused on the screen by means of the objective in the optical system of the galvanometer, but there must be a cylindrical lens so placed as to focus the beam of light in a sharp line on the screen. The method we have used for causing the beam of light to move on the screen is a revolving mirror. In planning the apparatus we found that

it would be necessary to have as many as six mirrors, for the following reasons: The screen on which the image is to be viewed must be far enough away from the surface of the mirror to permit an unobstructed view of it. We estimated that this should be not less than 5 cm. If the screen was closer than this the mirror would obstruct the view and necessitate looking at the screen too obliquely. With a single mirror revolving at a speed of 12 revolutions per second, as would be necessary to produce good visual fusion, the image of the string at a distance of 5 cm from the surface of the mirror would have a velocity of 7.5 meters per second. This would mean spreading out the curve of the action current, or indeed of any excursion which we might induce in the string galvanometer, so that the curve would appear almost as a straight line. The maximum velocity of the image at which the curve resulting from the excursion would have a convenient form for study is about 3 meters per second; for most purposes a speed of 2 meters per second or less is preferable. To render possible a slow enough speed of motion and at the same time to give sufficient frequency of repetition for visual fusion required six mirrors. The apparatus, therefore, was constructed with a hexagonal drum or spindle on which are mounted six mirrors silvered on the first surface.

The apparatus is driven by a motor making 1800 rpm. Since the mirror and the interrupter must turn over between 120 and 250 rpm, speed reduction is effected by transmission from motor to shaft through a double friction drive. At each stage of the friction drive transmission the speed ratio may be varied by shifting the wheel along the shaft between the center and the periphery of the disc. An additional advantage of the friction drive is the elimination of vibration which in the case of gear reduction would be apt to cause uneven rotation of the mirror. For accurate regulation of the speed while the apparatus is running, a rheostat with resistance variable up to 800 ohms is introduced in the armature circuit.

The essentials of the optical system are shown in Fig. 1. The beam of light passes first through a cylindrical lens and then is reflected from the surface of the mirror to a circular screen whose center of curvature is approximately the mean position of the mirror when reflecting the beam upon the screen. The screen is made of metal with rims at the sides under which a strip of paper can be inserted and thereby held in contact with the metal screen. For quantitative work in observing the magnitude or duration of deflection a strip of coordinate

paper is inserted in the slit. The cylindrical lens has a focal length of about 9 cm.

In order to repeat the excursion of the string in such a way that the deflections appear always at the same place on the screen it is necessary that the device which produces the nerve impulse should be synchronized with the rotation of the mirrors. The most convenient method of stimulating a nerve is by break shocks from an inductorium. To induce these a circuit must be broken. The apparatus is therefore constructed with a rotary interrupter with six conducting segments, mounted on the same shaft as the revolving mirror.

If interruption of the current is made simply by having a brush make contact alternately with conducting and insulating material, the unequal wear of the two materials by the brush is apt to cause irregularities of the surface, which will result in such vibration of the brush as

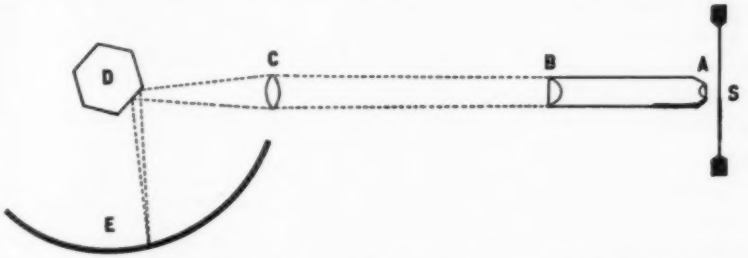

FIG. 1. *Simplified schema of optical system. Horizontal view. A. Objective. B. Ocular. C. Cylindrical lens in section. D. Revolving mirror. E. Viewing screen. S. String in galvanometer.*

may cause additional interruptions of the current when the brush should be making contact with the conducting segments. In order to minimize this effect insulating segments were replaced by "dead" segments of the same material as the conducting ones, insulated from them by thin segments of mica, only 0.5 mm in thickness. The conducting segments are made of phosphorbronze. Every other segment is connected with a slip ring on which another brush makes permanent contact, the alternate segments being completely insulated from it.

Erlanger and Garrey[5] showed the duration of make induction shocks to be as great as 0.032 sec. with certain coils. If, therefore, a nerve be stimulated with more than 16 pairs of make and break shocks per second, equally spaced, each break shock may begin before the preced-

[5] Erlanger and Garrey: Amer. Journ. Physiol., *35*, p. 403; 1914.

ing make shock has quite subsided. It is therefore desirable to be able to deliver the make shocks earlier than half way between successive breaks. In order to vary the time relation between successive makes and breaks of the circuit, the metal segments of the interrupter were made tapering, one side of each being parallel to the shaft, and the other side converging toward the first in a spiral. By shifting the brush along a track parallel to the axis of rotation the interval between make and break can be varied at will within limits, the range being from 41 to 74 percent of closure.

For observations on the refractory period of nerve it is necessary to apply two stimuli at a brief interval which may be varied at will. For this purpose two brushes insulated from each other are provided for making contact with the metal segments. One is mounted on a fixed track parallel with the shaft, and is therefore in a fixed position as regards the time at which it breaks the circuit. The other is so mounted that its time of breaking contact may be adjusted by rotating it forward or back on the axis of rotation of the mirror. The rotary interrupter is 5.2 cm in diameter and 8 cm long.

In order to have the curves thrown on the screen by the six mirrors perfectly superposed it seemed best not to trust the accuracy of the machine work, which would be necessary if the position of the mirrors were fixed. The mirrors, therefore, are mounted in slots in which their exact position can be determined by fine adjusting screws at three points, two at one end, and one at the other. Each mirror is held firmly against these adjusting screws by springs, one at each end. To make the shadow of the string when at rest always follow the same base line it is only necessary to make a fine adjustment in the screw at one end of the mirror. To make the excursion of the string resulting from the break occur at exactly the same point on the screen at each of the six breaks in the course of a revolution, it is necessary to make fine adjustments in the two screws at the other end of the mirror. In practice we have found it possible to superpose the curves of the successive breaks to within less than half a mm, which, when the mirror is revolving at 143 rpm, represents 0.2 σ of time. The visible curves are then sufficiently steady and well-defined for all practical purposes.

In using the apparatus for the study of refractory periods it is necessary to know the exact time interval represented by a given displacement of the movable brush. This will, of course, depend on the speed of rotation of the mirror. In order to determine the speed, an

electrically driven tuning fork making 100 double vibrations a second is placed in the path of the beam of light, so that its shadow falls upon the screen. If the speed of the mirror is so adjusted that the time of passing of a single segment (one-sixth of a revolution) is an exact multiple of 0.01 sec., the shadow of the tuning fork will appear to stand still in the form of a series of stationary waves; if the speed is greater or less, these waves will appear to move to right or to left across the screen. Since a 1% deviation in speed will cause a progression of the waves at a rate of one wave length per second, it is easy to make with the rheostat a relatively fine adjustment of the speed, guided by this control. With the friction drive adjusted for the most convenient amount of speed reduction, the 800-ohm rheostat gives a range of speeds including three at which the tuning-fork waves become stationary, viz.—111, 125 and 143 rpm. Once the time interval between the breaks of the two brushes has been determined for two or more positions of the movable brush at a known speed of rotation, a curve may be plotted which will give the exact time interval for every other setting of this brush. This was done by connecting the brushes in circuit with the primary coils of two coreless inductoriums, the secondaries of which were connected in parallel with each other and with the string galvanometer. The speed of the mirror was so adjusted that the tuning fork shadow appeared as a stationary wave. The length of this wave, representing 0.01 sec., was noted in terms of the number of squares of the coordinate paper which it covered. Then, at three different settings of the movable brush, the interval between the excursions which registered the break shocks of the two coils was read off directly, also in terms of the number of squares of the coordinate paper between them. From these readings the desired curve was plotted. The refractory period of a given nerve is measured by setting the movable brush where a second response barely appears on the screen while the mirror is revolving at a known speed, controlled by the stationary appearance of the tuning-fork waves, and then noting the setting of the movable brush. The time interval is then read directly from the calibration curve. The range of intervals available between the breaking of the circuits by the two brushes is from 0 to 0.036 sec.

It is possible to use the apparatus for the observation of regularly rhythmic currents from a source other than the interrupter which is synchronized with the mirrors. This may be done by regulating the speed of the mirror until the galvanometer excursions appear as station-

ary waves, as in the case of the tuning-fork vibrations. In this way it is possible to test the operation of an independent circuit breaker, if so desired, by connecting it with a source of current led into the galvanometer.

The entire apparatus is mounted on a wooden frame with the motor completely insulated from the shaft of the mirror and interrupter, and thus from the brushes which are connected with the stimulating circuit,

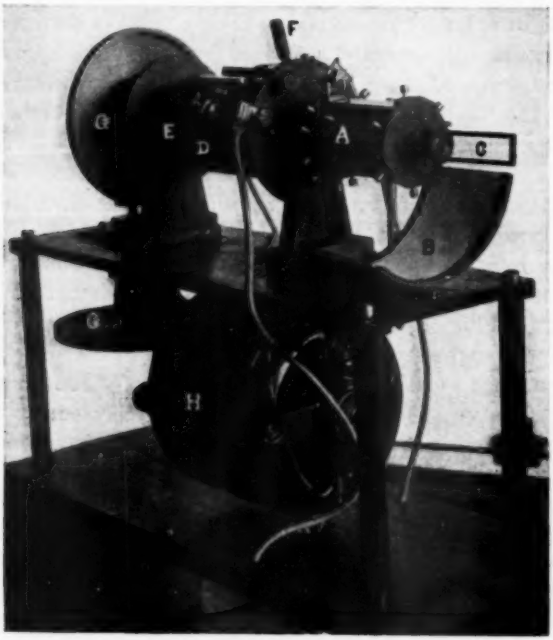

FIG. 2. *Photograph of apparatus. A. Revolving mirror. B. Viewing screen with coördinate paper in place. C. Cylindrical lens. D. Fixed brush. E. Rotary interrupter. F. Lever for adjusting movable brush. G. Discs of friction drive. H. Motor.*

or, in the case of calibration curves, with the galvanometer. The entire apparatus, excepting the rheostat, occupies a space on the table only 17×35 cm, and stands 43 cm above the table. A photograph of it is shown in Fig. 2.

If a high-speed photographic record of an action current is desired this may readily be made with the revolving mirror. It is difficult to obtain good records of single responses on a moving film at a higher

speed than 1 meter per second, and to make such a record at more than 50 cm per second without great waste of film requires a rather elaborate automatic shutter and stimulating device (cf. 3, p. 561). By using the revolving mirror a record may be made directly on bromide paper by laying it on the surface of the screen and exposing it to the repeated excursions of the shadow of the string for a few seconds. This is convenient for measurements of brief intervals in the record, since the horizontal motion of the shadow is about 2 meters per sec. A light-proof box has been made to fit the viewing screen, so that a strip of bromide paper may be placed close over the screen and exposed for the desired time by the removal of a shutter.

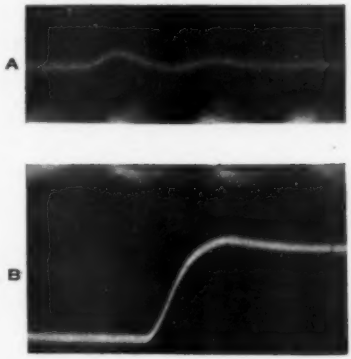

FIG. 3. *Photographic records made with revolving mirror directly on bromide paper. A. Action currents (monophasic) of popliteal nerve of cat. Temperature about 20°C. Two stimuli, both maximal, applied with interval of about 8σ; second response, occurring in relative refractory period, is subnormal. B. Calibration curve made by break of constant current,—6 millivolts sent through string.*

Hindle galvanometer with 1.5 mm air gap; 17,000-ohm string, diameter 2.75μ. Magnification 410. Tension of string, 104 m per amp. (see Forbes and Ray: Am. Journ. Physiol.; LXIV, p. 439, 1923). Time is shown by tuning fork shadow making 100 d.v. per sec. (Imperfect tuning fork shadow due to slight change of speed of mirror during part of exposure.)

Fig. 3 illustrates a record of action currents in nerve, together with a calibration curve, both made by this method. The nerve record shows the responses to two stimuli the second of which was applied during the relative refractory phase following the response to the first, so that the second action current was subnormal. The calibration curve was made by connecting one of the brushes with the cell which supplied current[6] to

[6] Forbes and Gregg: Amer. Journ. Physiol., *37*, p. 124; 1915, (see wiring diagram).

a slide wire from which a small current was tapped off and led through the galvanometer. Thus it represents the break of a constant current under conditions in the circuit comparable with those in an experiment with nerve. These illustrations serve to show examples of the use of the apparatus and the degree of refinement which it offers in photographic recording.

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The Cathode Ray Oscillograph and Its Application to the Exact Measurement of Explosion Pressures, Potential Changes in Vacuum Tubes and High Tension Magnetos.—The cathode ray oscillograph has until recently been used by allowing the electron stream to strike a fluorescent screen and then obtaining a photographic record with the aid of the light so generated. The small amount of light available makes a long exposure necessary so that this form of oscillograph has been restricted in its applications to a study of periodic phenomena. The novel feature of the instrument here described is that the photographic plate is placed in the vacuum tube itself in such a position that the narrow stream of electrons impinge directly on the plate. One traversal is sufficient so that transient as well as periodic changes can now be recorded.

The electrons are obtained from a heated filament surrounded by a metallic cylinder, as in the Coolidge x-ray tube and are accelerated to a sufficiently high speed by connecting a 6000-volt d.c. generator between the filament and a stationary metal plate. The latter has a fine opening in it which segregates a narrow beam of electrons. The beam then passes in succession through two sets of two parallel plates—the two sets being at right angles to each other. One pair of plates connected to a Vreeland oscillator, deflects the beam one axis by an amount which is a known function of the time; the other pair is connected to the emf to be studied and produces a deflection at right angles to the first axis. The beam then proceeds directly to the photographic plate. The apparatus is evacuated to a pressure of 10^{-3} mm of mercury.

The instrument is capable of measuring not only purely electrical phenomena but also, of course, any physical change which can be transformed into an emf. Photographs are shown of records made with this instrument of the pressure waves in water due to gun cotton and T.N.T. explosions. The emf's in this case were obtained by making use of the piezo-electric effect in tourmaline crystals.

The paper includes a photograph and drawing to scale of the apparatus together with several curves gotten with its aid. —[D. A. Veys, Jour. Frank. Inst., *196*, p. 577; 1923.]

LEO BEHR

A TORSION SEISMOMETER

J. A. Anderson and H. O. Wood

Introduction

The instrument described below was developed primarily for the study of earthquakes which originate within a radius of about 300 kilometers of the place of observation. After consideration of the requirements for this an instrument with a relatively short period and a rather high magnification seemed desirable.

For our first experiment, therefore, we constructed an instrument with a period of 0.3 second and a magnification of approximately 700. This recorded local shocks very well; and, to our surprise, it also recorded the initial phases of the stronger teleseisms, notwithstanding that the periods found in these, though short in some cases, were all longer than the period of the instrument. This indicated that, by lengthening the period two or three fold, it should be possible to improve the registration of teleseisms greatly without material sacrifice of accuracy in the recording of local shocks. Accordingly two instruments, with periods of about 0.8 second and magnifications of 1200 and 2400 respectively, were constructed and put in operation. The records obtained with these during the past six months have fully justified our expectations. Also a third instrument, having a period in the neighborhood of 5 seconds and a magnification of 1200, has been in regular use for several months. In general it records teleseisms much better than the instruments with shorter periods; but microseismic motion, with periods of 6 seconds or less, is very much in evidence,—in fact so much so that this is very often troublesome: and it registers the shocks of local origin not quite so well as do the instruments that have shorter periods.

From the experience gained up to the present time we reach the conclusion that the instrument best suited for the study of local earthquakes should have a period not greater than 1 second, should be critically damped, and should have a magnification as great as 2500 and possibly two or three times this value. Such an instrument will also serve very well for the study of important aspects of teleseismic motion. But for the adequate study of the L-phase of teleseisms an instrument having very different characteristics will be required.

DESCRIPTION

A torsion seismometer of the short-period type which appears to meet the requirements for the registration of local earthquakes is shown in perspective drawing in Fig. 1. This instrument is designed to record a horizontal component of the earth motion. A fine wire T fastened to and tightly stretched between the upper suspension lug U and the lower suspension lug L carries attached to it near its middle a copper cylinder C to which is fastened a small plane mirror m. (A somewhat enlarged view showing the arrangement of the cylinder, mirror, and

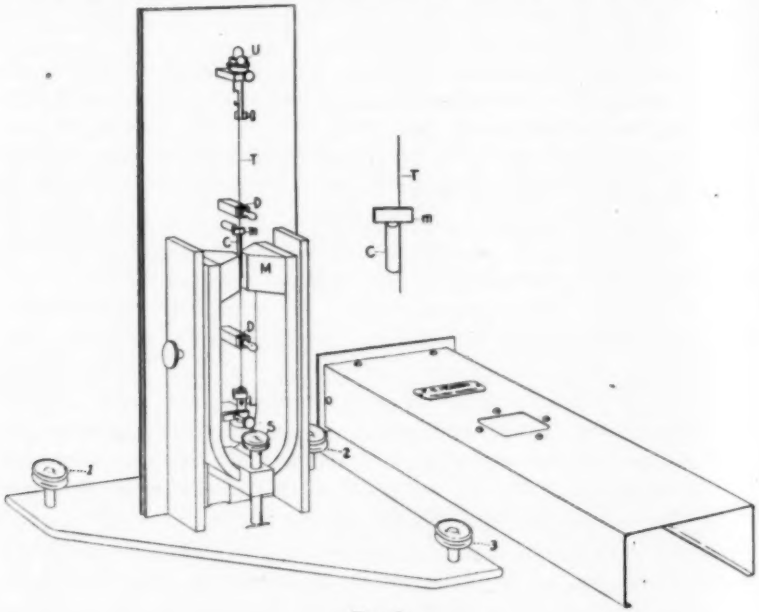

FIG. 1

wire is shown in the inset). T is a tungsten wire about 16 cm long with a diameter of 1/50 mm. T is drawn taut by the weight of the brass cylinder (amounting to about 15 grams) shown just below the clamp of the suspension lug L. The copper cylinder C is about 2.5 cm long and 2 mm in diameter and, with the mirror attached, weighs approximately 0.7 gram. As the inset drawing shows, the wire T is attached to the surface of the cylinder C parallel to its axis. When the wire T, taut and fastened to the suspension lugs U and L, is placed

exactly in the vertical, this system forms a strictly horizontal pendulum, with Cm as an eccentric inertia-mass, having its position of equilibrium determined by a restoring force due wholly to the torsion of the wire. When disturbed by horizontal earth-motion, rotation of the eccentric system takes place about the wire as an axis in a manner similar to other horizontal pendulums. Also a horizontal vibration, like that of a violin string, of relatively very short period, results from a sufficiently strong acceleration. In order to prevent this horizontal, or violin-string, vibration, or damp it out very rapidly, the wire T passes through two small drops of castor oil held in the "oil-dampers" DD. These oil-drops exert almost no damping on the *torsional* vibrations of the system which are set up by a horizontal earth motion. To realize the conditions of critical damping for *torsional* vibrations a permanent magnet M is so placed that the copper cylinder C is suspended in the air-gap between the pole-pieces of M, and so that the small oscillations of C about its equilibrium position take place at right angles to the magnetic field. The magnet may be adjusted vertically by means of the screw S. With M in its lowest position the cylinder C is entirely out of the field. In this position, since the damping is nearly zero, the undamped free period, T_0, may be determined. With M raised to its highest position the entire cylinder is in the field and the system is then somewhat overdamped. Thus by merely moving M vertically all conditions between nearly zero damping and aperiodicity may be realized.

ADJUSTMENTS AND CONSTANTS

We will now consider briefly the adjustments of the instrument and the determination of its constants.

Knowing the torsion constant, K, of the wire T, and the moment of inertia, I, of the system Cm, about T as an axis, the period of oscillation is given by the equation

$$T_0 = 2\pi\sqrt{I/K} \qquad (1)$$

K being the moment in dyne-centimeters necessary to rotate C through a unit angle from its position of rest. This assumes that T is truly vertical, that is, that the two points where T is fastened to the upper and lower suspension lugs lie on a vertical line. If the line just defined, which we will denote simply the line T, is not vertical there will be in general a moment about it due to gravity which may be expressed as follows. Take the middle point of the line T as the origin, O, of spherical co-ordinates. Let OZ, the polar axis, be the vertical through O, and let

the fixed line OA, at right angles to OZ, pass through the center of mass of the system Cm when this is in its equilibrium position. Denote the horizontal angle measured from OA by θ, and the vertical angle measured from OZ by i. Then, if the co-ordinates of the line T are (i,θ) the moment about T due to gravity is

$$\mu\, g\, l \sin i \sin\theta$$

where μ is the mass of the system Cm, and l is the perpendicular distance from its center of mass to the line T. As i in general will be a very small angle we may replace $\sin i$ by i and write for the moment due to gravity

$$M_g = \mu\, g\, l\, i \sin\theta \tag{2}$$

and for the total moment about T

$$M = -K\theta + \mu\, g\, l\, i \sin\theta \tag{3}$$

Now if the adjustment is such that T has the co-ordinates $(i=i,\ \theta=0)$ we shall have for small oscillations about the position $\theta=0$

$$T_1 = 2\pi\sqrt{I/K+\mu gli} \ < T_0 \tag{4}$$

and if the co-ordinates of the line T are $(i=i,\ \theta=\pi)$

$$T_2 = 2\pi\sqrt{I/K-\mu gli} \ > T_0 \tag{5}$$

In this case the system becomes unstable when $K=\mu gli$

When $i=0$, equation (3) shows that the system is at rest when $\theta=0$, —that is, when the center of mass of the system lies in the vertical plane through OA. Now let i be given a small value in the direction $\theta=\pi/2$. From (3) it follows that the system will now come to rest in the position

$$\theta = \mu gli/K \tag{6}$$

The Adjustment of the Instrument

The adjustment of the instrument involves the untwisting of the torsion wire T and placing it in a vertical position in such a way that the line drawn from the origin through the center of mass of Cm shall be parallel to the magnetic field in the air-gap,—or, what is nearly enough the same thing, until the normal to the mirror m is at right angles to the field. With U clamped, the clamp-screw of L is loosened and the instrument is levelled until the small cylindrical part of L hangs freely in the open clamp. The wire T will then untwist,—slowly, on account of the large inertia of L,—and will finally come to rest in a definite position. Suppose that in this position the angle between the normal to the mirror m and the magnetic field in the air-

gap is not a right angle. It can be made so by loosening the proper set-screw of U and rotating the whole system the required amount. After this is done U and L should be clamped. Adjustments must then be made to place T in the vertical again, for the operations of clamping will nearly always leave it inclined more or less. Let the cylinder C be to the left of T as shown in the figure and the inset. Lower the levelling screw marked *1* causing the instrument to tilt toward the left, about the line defined by the screws *2* and 3, through a considerable angle. On account of the large angle i thus introduced the period, as given by equation (4), will be quite short. Now if the line T lies in the vertical plane normal to the line $2-3$ the system Cm will not rotate when the base is elevated by means of screw *1*; in general, however, it will be found that on raising the screw *1* the system will rotate. If the rotation is clockwise screw 3 should be lowered, if counterclockwise screw 3 should be raised (or *2* lowered) until the indicated adjustment has been perfected. Then screw *1* is raised until the period T_0 has the value given by equation (1). Finally the magnet is adjusted until the damping has the required value. During the operation of levelling it is desirable to have the cover in place in order to avoid displacements of the system due to air currents.

DETERMINATION OF CONSTANTS

Assume that the instrument is to measure the x component of the earth's motion parallel to the line $2-3$. From the theory of the seismometer we know that its response to the x component of any earth acceleration is determined by three constants, namely, the free period T_0, the angular displacement θ_0 produced by a constant linear acceleration A_x equal to unity, and the damping constant h. (From these constants the so-called magnification of the instrument is derived). The determination of T_0 and h requires no comment here. To find θ_0 it is necessary to measure the steady deflection when the instrument is tilted through an angle i_x by means of screw 3; a reading is also taken when the instrument is tilted through an angle i_y by means of screw *1*. The latter deflection should be zero or nearly so. Corresponding to i_x the constant linear acceleration is gi_x and if this produces an angular deflection θ_x we have immediately

$$\theta_0 = \theta_x / g i_x$$

In case the deflection corresponding to the tilt i_y is not zero, but θ_y we have

$$\theta_0 = \frac{1}{g}\sqrt{\theta_x^2/i_x^2 + \theta_y^2/i_y^2}$$

and the instrument is adjusted to measure a component of the earth's motion which makes an angle ψ with the x axis given by

$$\tan\psi = \frac{\theta_y/i_y}{\theta_x/i_x} = \frac{\theta_y i_x}{\theta_x i_y}$$

General Remarks

It is obvious that this instrument is designed to register photographically, and so requires an optical system and a recording system not here described. Aside from this,—the seismometer proper is very little larger than an ordinary galvanometer, having a moving system whose mass is about 0.7 gram, and it can be moved about from place to place and adjusted with about the same facility as such an instrument.

Since, as is shown by equation (6), θ changes very rapidly with the angle i it is necessary to mount the instrument on a solid support such as a well made pier; when so mounted it is found to maintain its zero position very accurately. With registration at a distance of two meters the change in zero during twenty-four hours is inappreciable.

Equations (4) and (5) show that for a given instrument the period T_0 may be varied through a considerable range by introducing a gravity component in the plane $\theta=0$; with any such change in period it is, of course, necessary to readjust the magnet if the damping is to remain at the same value.

The instrument is easy to construct, since the only practical difficulty is that of having the moving system as free as possible from ferromagnetic material, the requirement in this respect being similar to but not quite as exacting as in the case of a high sensitivity galvanometer.

For the registration of the vertical component of the earth motion a similar system with the wire T in the horizontal position may be employed,—but this has been found satisfactory only for a period of 0.5 second or less. For longer periods a different principle is utilized which will be described in a future paper.

An instrument for the horizontal component, having a period, T_0, of 10 to 20 seconds, with a moving system considerably larger though not much heavier than that described above, but with a magnification of only 200 to 500, is quite possible, as shown by a rough model recently constructed. This should be useful in a study of the L-phase of teleseisms.

PASADENA, CAL.

OPTICAL SOCIETY OF AMERICA

Treasurer's Report

For the Period from December 1, 1922 to December 31, 1923

Receipts

Cash on Hand December 1, 1922	$ 5,961.63
Dues in Arrears	965.00
Dues for 1923	1,511.34
Dues for 1924	15.00
Life Membership Dues	100.00
Donations	3,005.30
Interest on Bank Balances	246.27
Journal Subscriptions from Subscribers on Books Prior to Feb. 15, 1922	589.27
Advertising	655.00
Sale of Journals-Back Numbers	469.39
Sale of Colorimetry Reports	4.42
	$13,522.62

Disbursements

Printing and Stationery	$ 875.23
Postage and Incidentals	88.13
Association of Scientific Apparatus Makers of United States Contract	4,609.12
Journal Subscriptions Since February 15, 1922	332.00
Cash on Hand December 31, 1923	7,618.14
	$13,522.62

I certify that the above report is correct to the best of my knowledge and belief.

(Signed) Adolph Lomb,
Treasurer.
Rochester, New York,
January 15, 1924.

Adolph Lomb, Treasurer,
Optical Society of America,
Rochester, New York.

Dear Sir:

In accordance with your request, we have audited the books of the Optical Society of America for the thirteen months ending December 31, 1923.

We hereby certify that the above report of Cash Receipts and Disbursements is a true statement for the period from December 1, 1922 to December 31, 1923.

Respectfully submitted,
Naramore, Niles & Co.,
Auditors.

FINANCIAL REPORT OF THE JOURNAL OF THE OPTICAL SOCIETY OF AMERICA AND REVIEW OF SCIENTIFIC INSTRUMENTS

FOR THE PERIOD APRIL 1, 1923 TO DECEMBER 31, 1923, INCLUSIVE

RECEIPTS

CASH ON HAND APRIL 1, 1923		$ 2,424.10
TO APPLY ON CONTRACT OF THE OPTICAL SOCIETY		
SUBSCRIBERS ON BOOKS PRIOR TO FEBRUARY 15, 1922	$ 435.77	
SALE OF BACK NUMBERS OF VOLS. I-V	361.39	
ADVERTISING COLLECTED FOR OPTICAL SOCIETY	275.00	
PAYMENTS FROM TREASURER OF THE OPTICAL SOCIETY	2,476.46	
SALE OF REPORTS OF COMMITTEE ON COLORIMETRY	4.42	
Total		$ 3,553.04
TO APPLY ON CONTRACT OF THE ASSOCIATION OF SCIENTIFIC APPARATUS MAKERS OF THE UNITED STATES OF AMERICA		
ADVERTISING		8,238.00
MISCELLANEOUS RECEIPTS		
SUBSCRIPTIONS SINCE FEBRUARY 15, 1922	763.30	
SALE OF BACK NUMBERS OF VOLS. VI AND VII	165.11	
SUNDRY ITEMS	23.35	
Total		951.76
Grand Total		$15,166.90

DISBURSEMENTS

PRINTER	6,692.31	
SALARIES	3,135.64	
SUPPLIES	79.34	
MISCELLANEOUS (POSTAGE, ADVERTISING)	544.82	
Total		10,452.11
CASH ON HAND		4,714.79
Grand Total		$15,166.90

The above is a correct statement of accounts to the best of my knowledge and belief.

(Signed) F. K. Richtmyer, Business Manager

We, the undersigned, duly appointed to audit the accounts of the Journal of the Optical Society of America and Review of Scientific Instruments as at the close of business, December 31, 1923, hereby certify that we have examined the statement of receipts and disbursements, the vouchers, check book and bank book and find them to agree with each other. We therefore certify that the above statement is a true statement of the accounts of the Journal of the Optical Society of America and Review of Scientific Instruments as of December 31, 1923.

(Signed) Casper L. Cottrell
Walter H. Stainton

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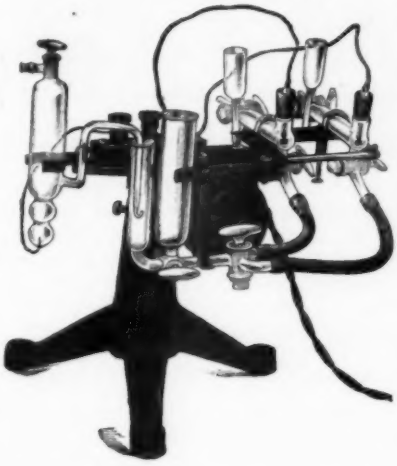
WHITE, WALTER P.: A Superior Electric Pendulum; and Some Pendulum Equations, 767.
WOOD, H. O. and J. A. ANDERSON: A Torsion Seismometer, 817.

X

X-Ray Apparatus (Samuel K. Allison and George L. Clark), 681.
X-Rays, A Measurement of the Polarization of Secondary (Arthur H. Compton and C. F. Hagenow), 487.

Hydrogen Ion Apparatus



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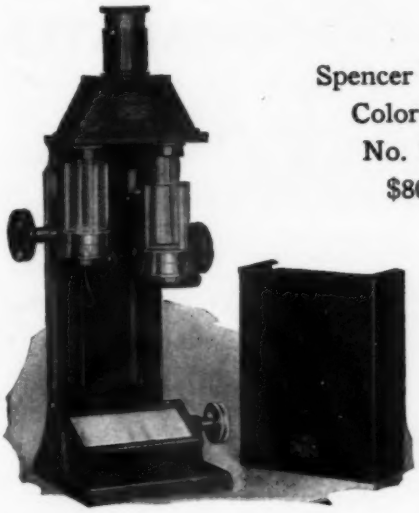

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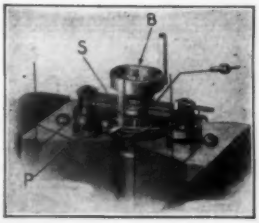

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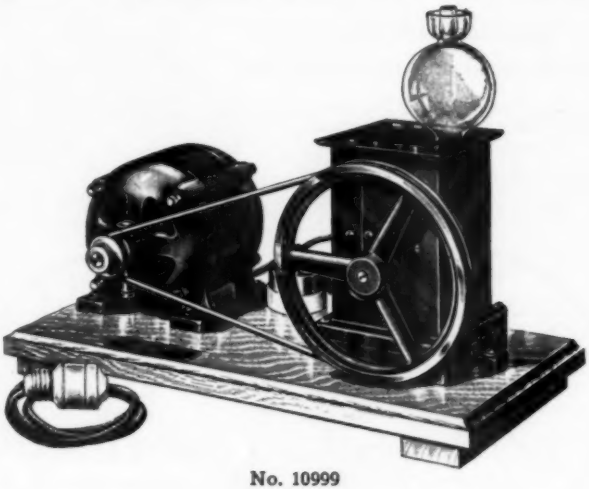

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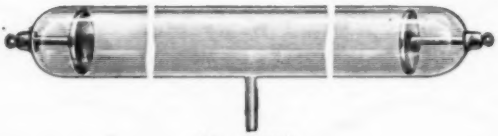

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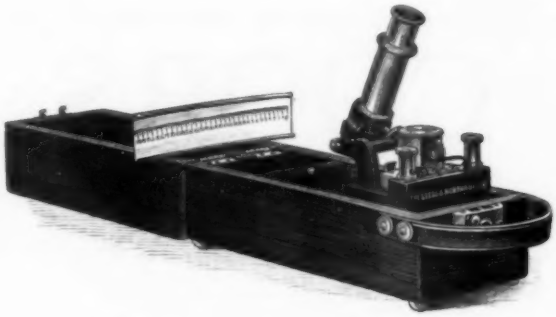

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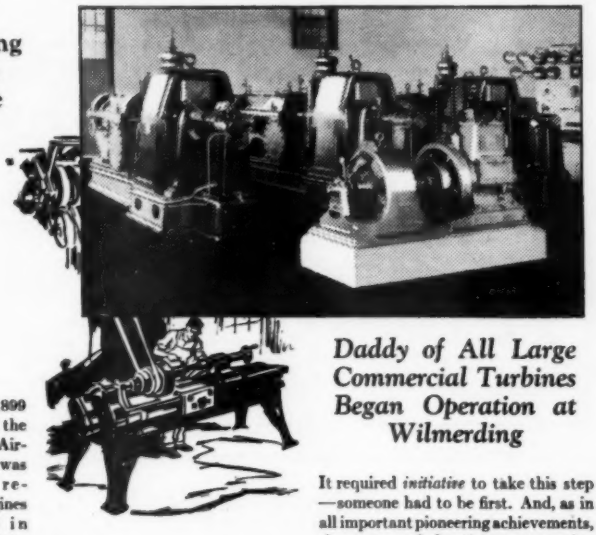

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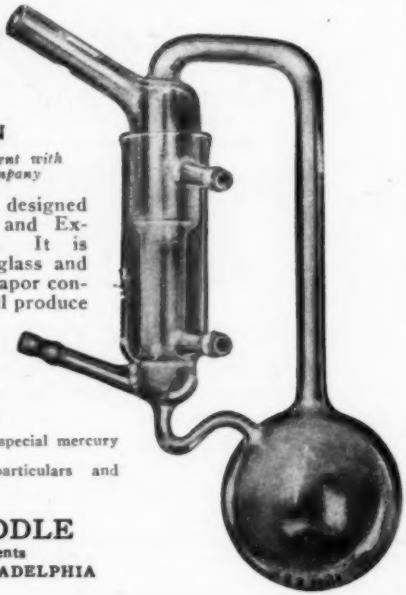

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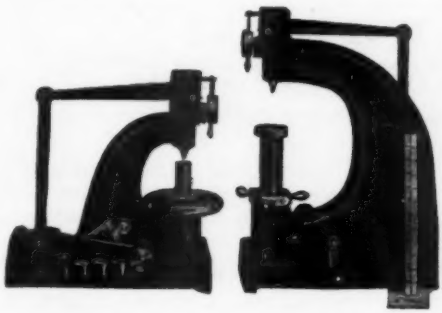

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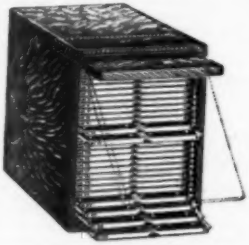

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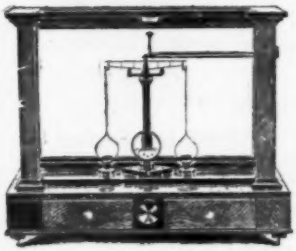

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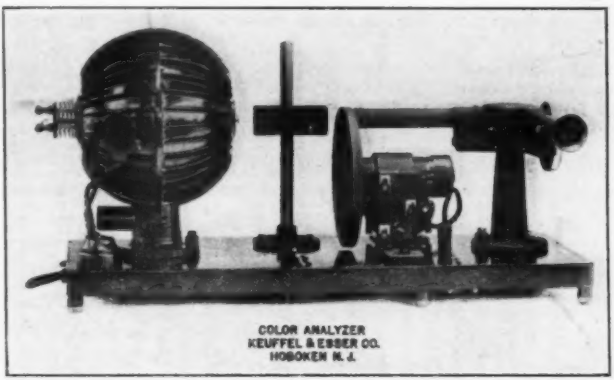

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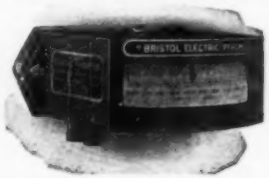

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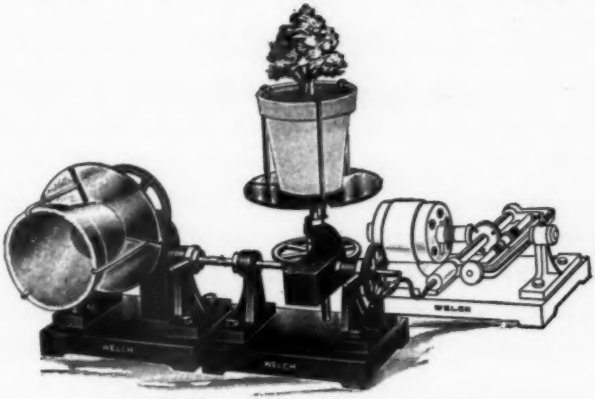

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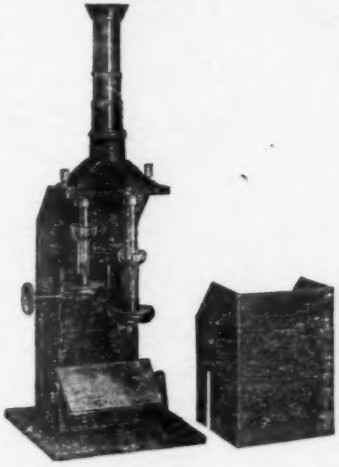

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